INFLUENCE OF FUELBED AND VENTILATION PARAMETERS ON SMOKE AND TOXIC GAS PRODUCTION IN ENCLOSED SHIPBOARD FIRES

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13. ABSTRACT

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The data indicates that during the intense phase of combustion optically dominant smoke particle sizes are somewhat less than 400 nm but increase during die-down. Smoke production per unit mass fuel consumed seems to increase with burning intensity, but more data is needed to quantify this. Observed CO concentrations were somewhat less than initially anticipated.

An important experimental observation was the coupling between volumetric flow increase due to heating and system ventilation. It is conjectured that such coupling could lead to unexpected smoke accumulation from shipboard fires.

The fire chamber has been adapted to make possible controlled application of water spray, carbon dioxide and Purple K from an easily changeable location. Results of a series of pilot fire suppression runs are presented.

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Abstract

Smoke and toxic gas production by enclosed shipboard fires is modeled in a 6×6×6 ft fire chamber in which fuelbed and ventilation parameters can be readily adjusted. Smoke is characterized primarily by obscuration characteristics and the toxic gas so far investigated is carbon monoxide CO. For runs to date the fuel has been kerosene, although many other fuels and fuel combinations can and will in the future be burnt.

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An important experimental observation was the coupling between volumetric flow increase due to heating and system ventilation. It is conjectured that such coupling could lead to unexpected smoke accumulation from shipboard fires.

The fire chamber has been adapted to make possible controlled application of water spray, carbon dioxide and Purple K from an easily changable location. Results of a series of pilot fire suppression runs are presented.

Introduction

This report describes an investigation aimed at problems related to suppression of enclosed shipboard fires. The project is an outgrowth of a study of modeling of enclosed shipboard fire suppression by F. A. Williams and R.C. Corlett[1]*. This work has been coordinated with related research at the US Naval Weapons Center, China Lake, California, under the supervision of Dr. A. S. Gordon and a parallel contract to the University of California, San Diego, whose Principal Investigator is Dr. F. A. Williams.

The major thrust of the program described in this report is directed towards an understanding of smoke and toxic gas production in enclosed shipboard fires. In general, smoke and toxic gas present a direct hazard to firefighters and others in the vicinity of a fire. The necessity to avoid the damaging and discomforting effects of smoke often places a serious constraint on firefighting operations.

Moreover, there is an indirect effect due to loss of visibility. Even if adequate protection is available, it may not be possible to see the fire clearly or to make the best decision for dealing with it. In extreme cases, smoke accumulation may make it difficult even to find the fire. Smoke also renders difficult movement from place to place within complex structures or escape from them. It is possible to be "lost" in smoke with fatal consequences.

Smoke and toxic gas production in enclosed shipboard fires, particularly deep in the interior of large vessels such as aircraft carriers, introduces special problems. For one thing, escape routes and travel paths in support of firefighting efforts are usually above the fire, where smoke is encountered

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* Raised parenthesized numerals denote references at the end of this report.

relatively easily. Moreover, the types of materials encountered are to some extent unique to ship systems. Finally, there may be operational requirements which require that some regions, in particular that of the main power plant, continue to function even in the presence of severe fire.

In dealing with smoke and toxic gas produced in enclosed shipboard fires, a variety of steps may be taken. These steps fall into two main classes. One class encompasses firefighting equipment and tactics. The other may be characterized as the design of ships and the associated equipment. The first class includes fire warning and other diagnostic subsystems. The second class includes such matters as material selection, and specification of ventilation networks and capacity.

For either of the two broad classes of activity indicated above, a reasonable predictive knowledge of smoke and toxic gas production, accumulation and dispersion is required. The desired predictive knowledge is both quantitative and qualitative. As is discussed in Section 2.1, it is not clear how to characterize smoke with regard to either quantity or quality. But whatever characterization is adopted can be regarded as the "output" of smoke and toxic gas production. What is desired is the ability to determine this output as a function of relative "input" variables. These input variables are numerous, including the amount and type of combustible materials involved, length scale, ignition and fire development patterns, extent of ventilation, and the nature of fire suppression efforts.

Disregarding for the moment the question of how smoke may be quantified, we can split the problem of smoke and toxic gas into two pieces. One piece is the production. How much is generated by the fire? The other piece is dispersion and dilution. Where does the smoke go and in what concentration? The dispersion and dilution problem can be divided further, into consideration of the enclosure

where the fire actually occurs and of downstream phenomena in passageways, shafts, etc. The latter problem is beyond the scope of the present work.*

From most practical viewpoints, the smoke and toxic gas generated by a fire may be characterized by some measure of concentration and a volume rate of gas flow from the enclosure (or, generally, from each exit). For purposes of modeling, it is of interest also to characterize smoke production also as a production rate per mass fuel consumed. Some ideas of smoke rating of materials rest on the tacit assumption that the "amount" of smoke produced per mass fuel consumed is a property of the material. This is clearly not an absolute truth. But even if only a rough approximation to reality, this would reduce the problem of smoke production to a problem of burning rate prediction.

A major goal of this research program is understanding of smoke production as a function of fire variables, of smoke and toxic gas production as characterized by both of the above viewpoints. The principal fire parameters investigated are degree of ventilation, and fuelbed characteristic length.

Section 2 describes the experimental system developed in this program. This system consists of a 6x6x6 ft (180x180x180 cm) enclosure with suitable diagnostic and monitoring instrumentation. In the work so far performed the fuel has been kerosene in pans. Section 3 presents results to date. Section 4 is a discussion of the implications of these results and requirements for a relatively decisive picture. An extensive series of production runs including electric cable bundles as fuel is now ready for implementation.

A secondary objective of this project is a pilot investigation of modeling of fire suppression in enclosures. The enclosure has been equipped to apply a

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* An approach is outlined in Chap. 5 of Ref. 1.

variety of suppressants in a controllable variety of manners. This capability and the results of a pilot sequence of suppression tests are described in Section 5.

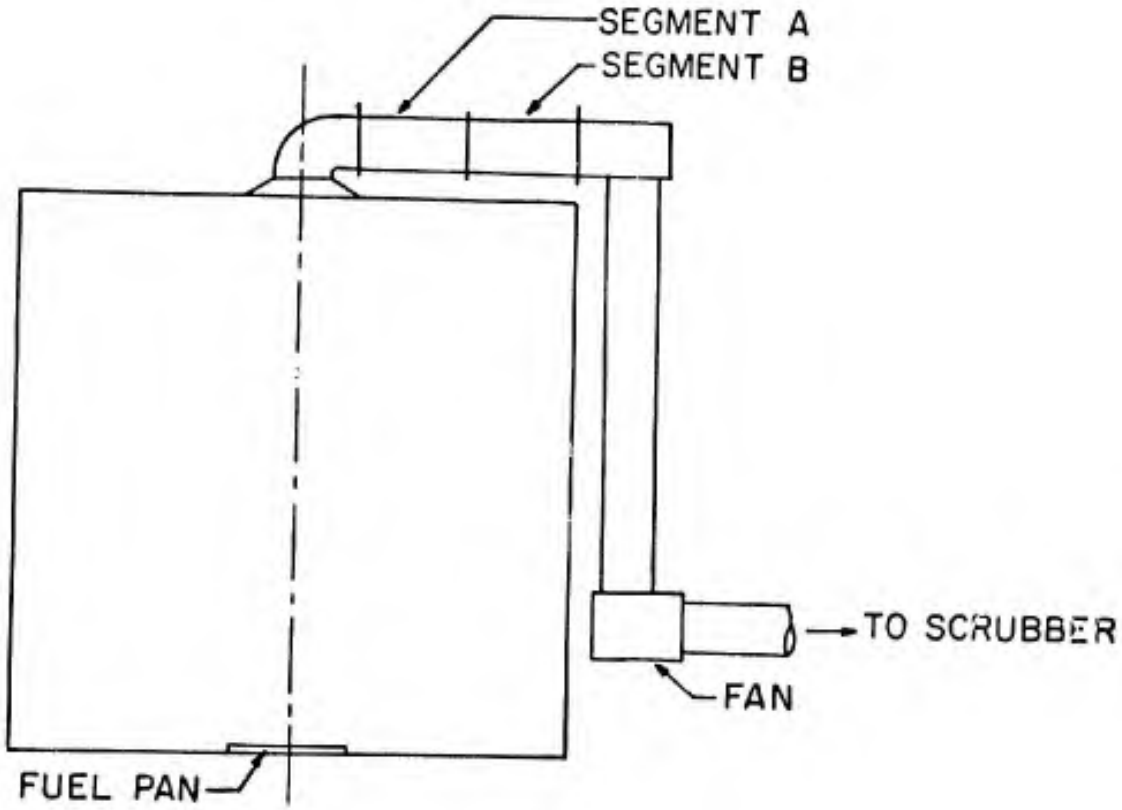
Section 6 contains some concluding statements. Added as an appendix is a paper by R. C. Corlett and T. I. Yu, "Modeling Hypotheses for Smoke Production in Enclosed Fires", presented at the 1972 Fall Meeting of Western States Section/ The Combustion Institute at Naval Postgraduate School in Monterey, California on October 30 and 31.

2.0 The Experimental System

Fig. 1 shows schematically the system developed in this project. Experimental fires are expected in a cubical chamber six ft (180 cm) on a side. The chamber is constructed of handy angle framework with asbestos board floor and sidewalls up to 5 ft elevation, and quartz fiber panels rated to withstand at least 3000°F (1600°C). The sidewalls are constructed of a number of panels which can be removed arbitrarily for ventilation purposes. On one side of the chamber a door is provided for easy access. On the same side as the door, a small quartz plate viewing port is installed at bottom right.

All of the gases which enter the fire chamber are pumped by a fan out through a single exhaust duct. The fan is downstream, to maintain negative gage pressure in the chamber. The chamber is not air tight, and even with no vent panels removed and the door closed will leak enough air to maintain a modest fire, with the fan at maximum setting. It is recognized that the single exhaust line with leaked inlet air is the reverse of many shipboard systems. However, it is felt that the present arrangement does not introduce any fundamental changes in the essential fire phenomena, while greatly facilitating quantitative studies of smoke production. If desired, a single inlet duct can be installed to provide room air, exactly simulating shipboard air supply systems. It is remarked that if a vent panel is removed, or a duct is passed through a wall or ceiling, the negative pressure in the chamber cannot reach large enough values to cause significant distributed leakage.

The exhaust duct is mounted on the top center of the chamber as shown in Fig. 1. The inside dimensions of this rectangular duct are nominally 6x12 in (15x30 cm). Segment A of the duct, shown at the bottom of Fig. 1, contains a two-dimensional contraction decreasing duct height from 6 to 1 in over an 8-in



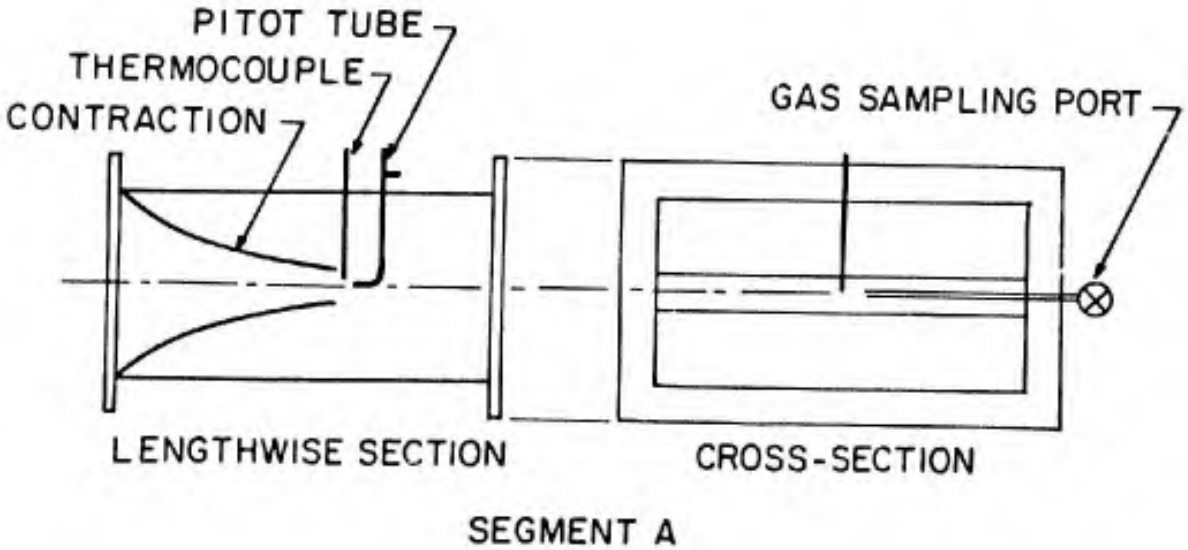


FIGURE 1 OVERALL EXPERIMENTAL SYSTEM AND BLOWUP OF SEGMENT A OF THE EXHAUST DUCT

length, resulting in an increase in exhaust gas flow velocity. A pitot tube, a thermocouple and a gas sampling port are positioned at the exit of this contraction where the gas flow velocity reaches a maximum. The purpose of the contraction is to facilitate monitoring of static and total pressure head at low mass flow rates. Segment B of the duct is reserved for the optical instrumentation described in Section 2.1. Finally, as the exhaust gases flow down the duct, they pass through a scrubbing stage which effectively removes the majority of the smoke. The scrubber consists of a series of finely atomized water sprays directed both parallel and opposite the flow direction. The fan is presently upstream of the scrubber, which has only recently been installed, and checked out. The fan will shortly be moved downstream to minimize heating by exhaust gases. Fan failure due to overheating has been a source of worry but has not yet occurred. Eventually, however, larger fires in the chamber will lead to temperatures well over 1000°F (or over 500°C) so that fan protection would be an obvious necessity.

Figs. 2 through 6 are photographs of the apparatus.

Experiments to date have been limited to liquid pool type fires with kerosene as the primary fuel and a small quantity of gasoline added to facilitate ignition. Square stainless steel pans, 1×1 and 2×2 ft, have been used. For definiteness, the pans have been located at the center of the chamber floor. In future use a variety of other locations are anticipated. Furthermore, other fuels, such as electric cable bundles, bedding, or oil-soaked insulation, will eventually be burned in conjunction with kerosene pan-burning.

Ignition of kerosene pans is accomplished with an automotive-type spark plug mounted on a retractable beam manually actuated from outside the chamber. The igniter is shown in extended position just above the pan in Fig. 3.

During the course of a run, the temperature, static pressure and total

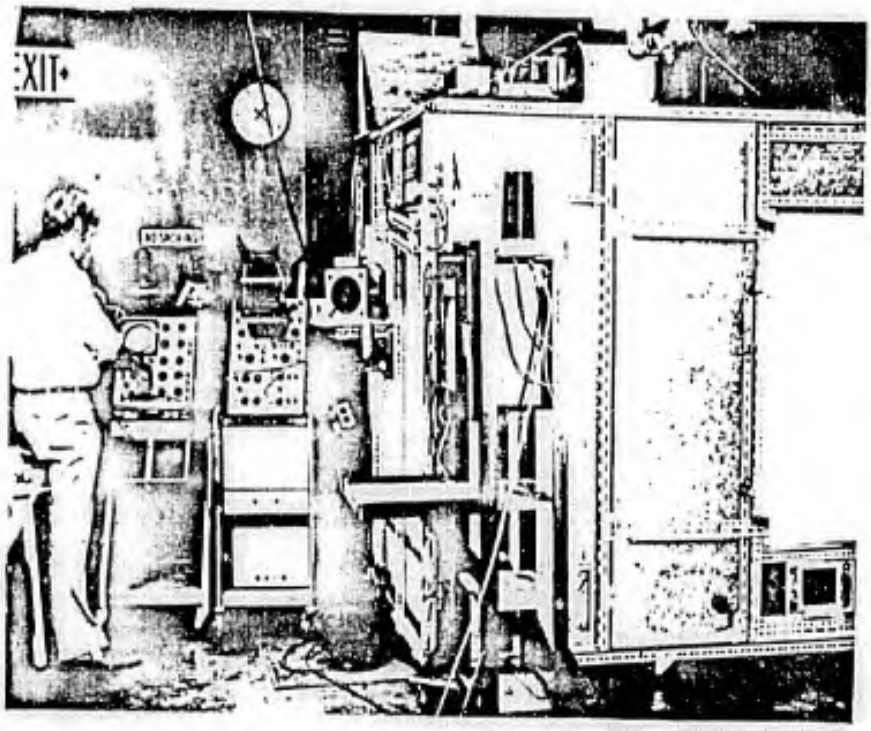


FIGURE 2 PHOTOGRAPH OF COMPLETE SMOKE CHAMBER

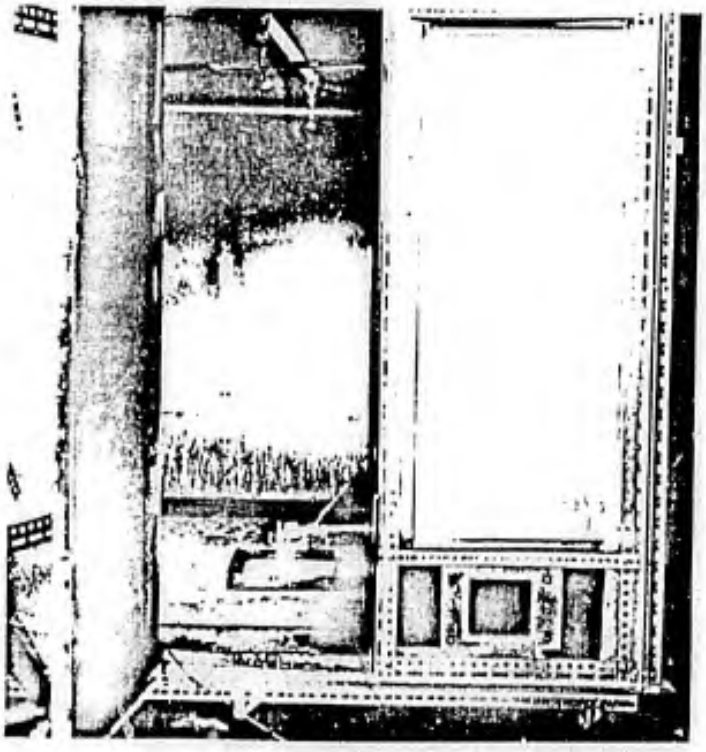


FIGURE 3 PHOTOGRAPH OF SMOKE CHAMBER INTERIOR WITH 1×1 FT PAN ON FLOOR CENTER

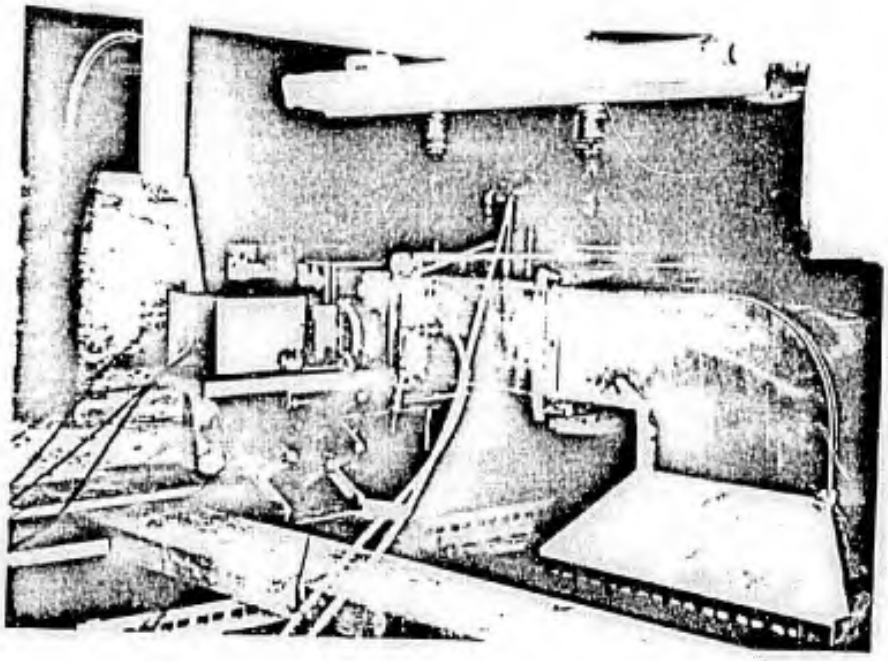


FIGURE 4 PHOTOGRAPH OF EXHAUST DUCT

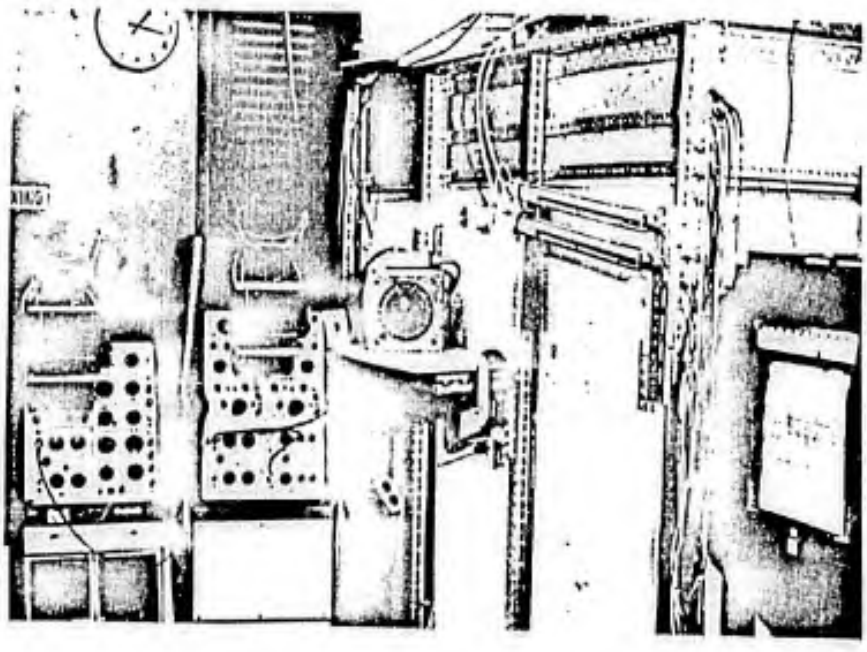


FIGURE 5 PHOTOGRAPH OF FLOW MONITORING EQUIPMENT

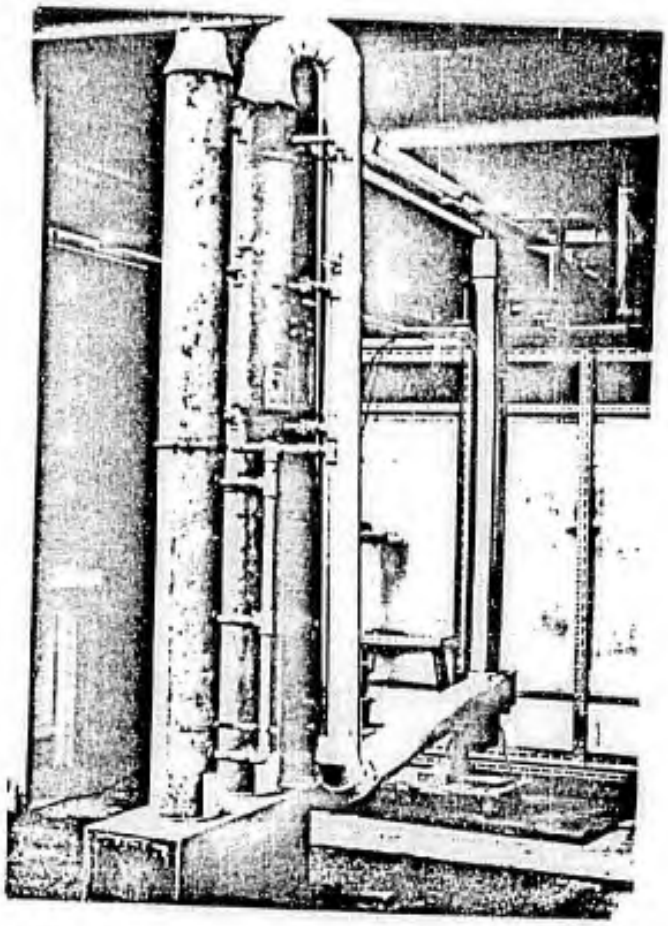


FIGURE 6 PHOTOGRAPH OF EXHAUST SCRUBBER

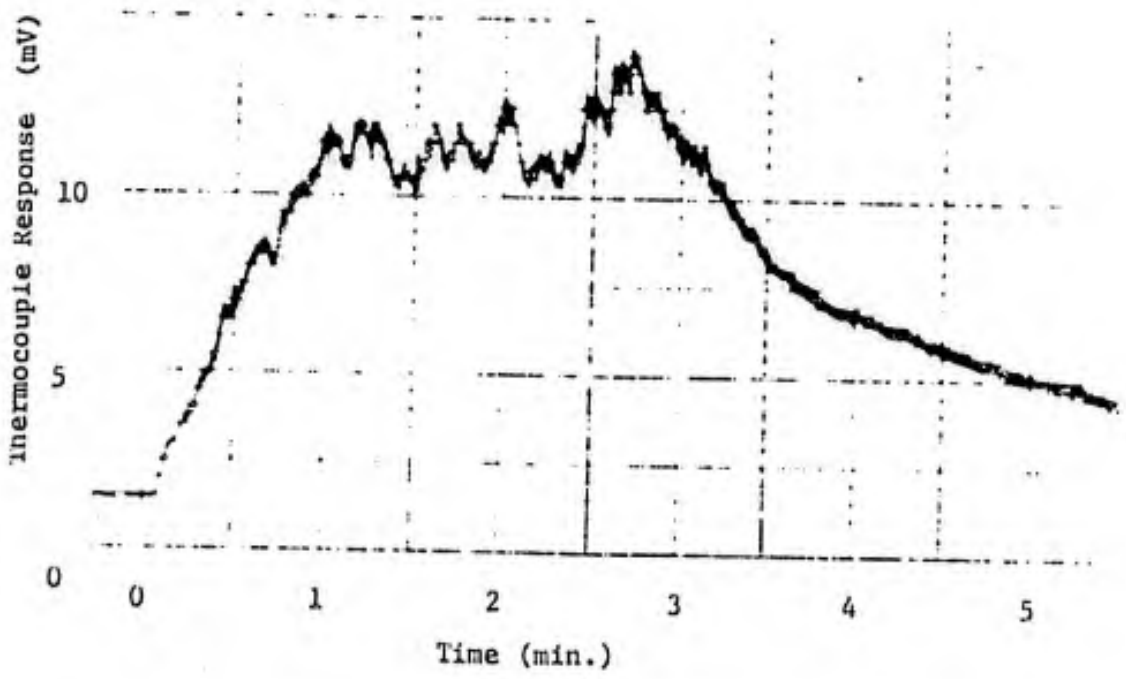


FIGURE 7 TYPICAL RAW EXHAUST TEMPERATURE RECORD

pressure of the exhaust gases are continuously monitored. This makes possible the determination of the total gas flow rate through the chamber and of the rate of sensible energy released by combustion. Typical raw temperature data in the form of a recorder trace is shown in Fig. 7. Pressure data, continuously monitored by two water manometers, is manually recorded at 30 sec intervals. All of this information is manually transferred to punch cards and the reduced data finally prepared as computer output.

2.1 Smoke Measurement

The quantitative characterization of smoke is a subject of considerable uncertainty. In principle, smoke can be characterized by particle size distribution, particle structural characteristics, and chemical composition (which may well vary with size). Also, toxic gases, such as carbon monoxide, CO, and hydrocyanic acid, HCN, are frequently considered as part of the smoke. In this work, toxic gases are studied by analysis of samples, as described in Section 2.2.

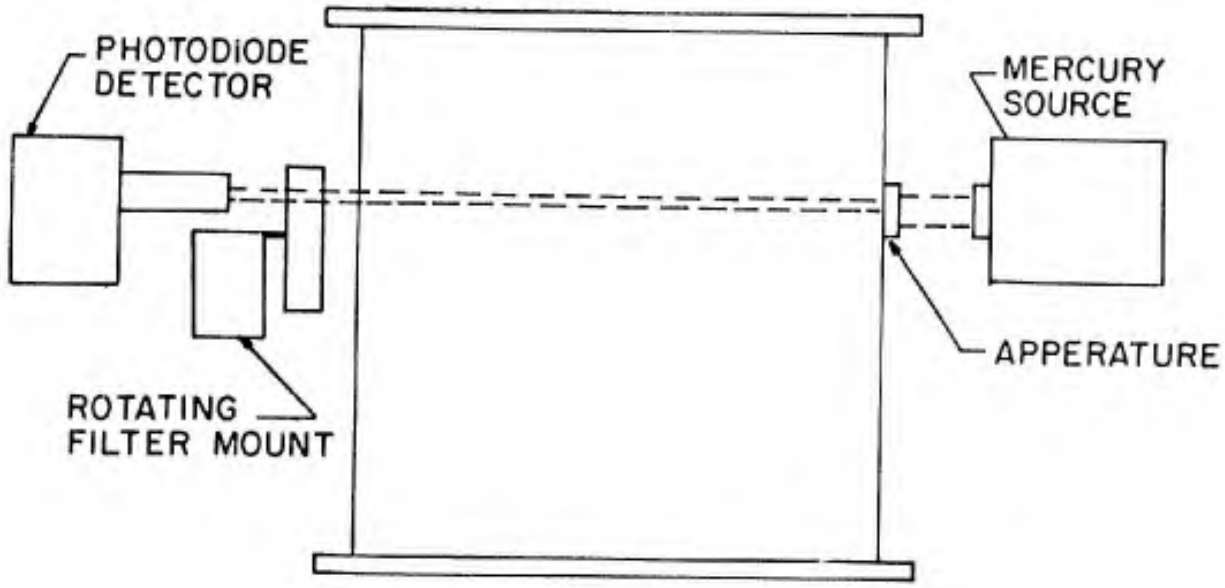
To avoid complex experimental development beyond the scope of the project, the decision was made to use optical transmission measurements as the primary characterization of smoke concentration. Four wavelengths, 400, 540, 700 and 1000 nanometers (nm), were selected. This set of wavelengths covers the visible range and gives some indication of the particle size distribution. It is recognized from fundamental work on optical scattering by particles (2,3) that the information thus obtained is insufficient to completely determine the complete size distribution. Scattering methods (2-6) are much more effective in this regard but were unfeasible in view of the budget and time scale of the project.

The optical system for transmission measurements is indicated schematically

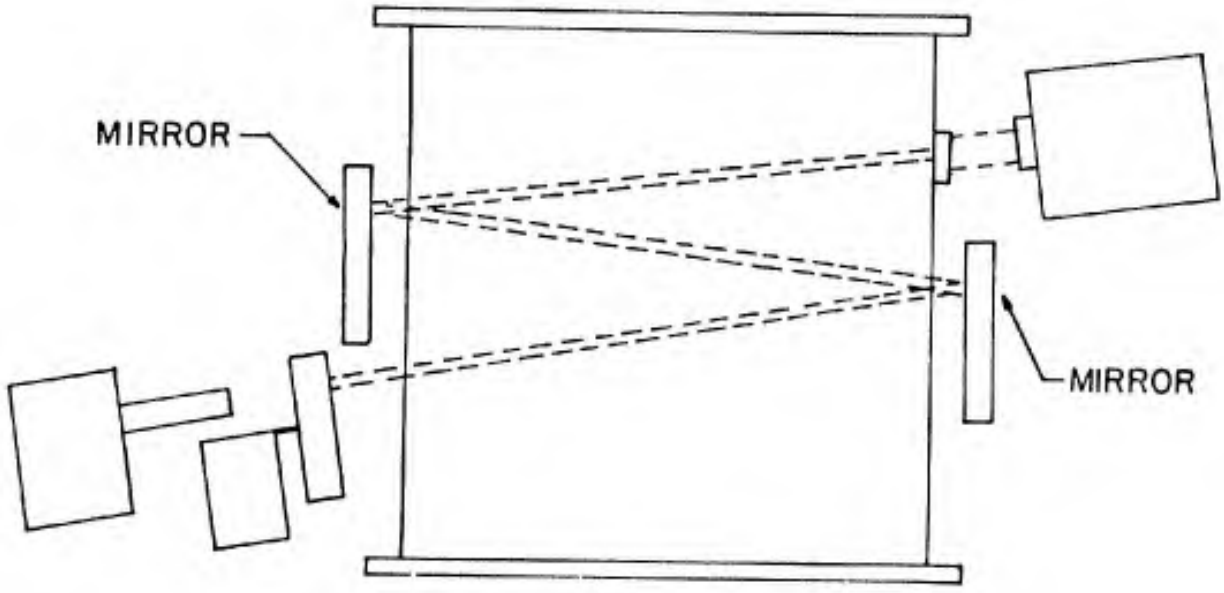
in Fig. 8, as installed in Segment B of the exhaust duct shown in Figs. 1 and 4. At the top of Fig. 8 is the normal layout of this system with a single 1 ft light path through the exhaust gases. In order to have the capability to increase optical path lengths for efficient measurement, the folded light path configuration, shown at the bottom of Fig. 8, was developed. This folded light path system is operational, but for most of the runs to date, single path measurement has been more suitable.

The components of the optical system consist of a mercury light source, a rotating amount housing four 10 nm bandwith interference filters, corresponding to the wavelengths of interest, and a photo diode detector. The rotating amount is visible on the laboratory jack in Fig. 4. The light source is a PEK 911 with accompanying model 401 power supply. The lamp housing includes the necessary collimating optics. The rotating filter mount is positioned normal to the beam emerging from the duct. The filters were purchased from Oriel Optics Corporation. The photo diode detector, RCA No. C30814, exhibits fast response time and adequate spectral response throughout the region of interest. The signal produced by the photo-diode detector is displayed on two Tektronix oscilloscopes, a No. 545A with Type D plug-in, and a No. 555 dual-beam with Type D and CA plug-in.

This system produces continuous and sequential pulses, proportional to the light passed by the four interference filters. The lower trace of the dual-beam oscilloscope and the single trace of the remaining oscilloscope are adjusted to identical magnifications and continuously monitor the signals produced by the optical system. The signals recorded at 540, 700 and 1000 nm are of similar amplitude while the 400 nm signal is considerably weaker. For this reason, the upper trace of the dual-beam oscilloscope is amplified to monitor the latter signal alone.



SINGLE LIGHT PATH CONFIGURATION



FOLDED LIGHT PATH CONFIGURATION

FIGURE 8 OPTICAL TRANSMISSION MEASUREMENT SYSTEM

Fig. 9 shows example oscilloscope traces. The two traces of the dual-beam oscilloscope are in phase, facilitating the later identification of signals. Prior to and following each experiment, a photographic record is made of the optical systems' response in the "no-smoke" mode. During an experiment, data acquisition is accomplished by photographing the oscilloscope traces.

At the bottom of Fig. 9 is "no-smoke" response. At the top of Fig. 9 is response of the system during part of a typical burn. Comparison of the two pairs of traces indicate substantial attenuation due to the presence of smoke.

The total amount of particulate matter formed, on a mass basis, is also of considerable interest. Although such a quantity does not necessarily correlate with the visible or physiologically dangerous characteristics of smoke, since these characteristics are dominatedby relatively small particles, it would be a good indication of the amount of unbound carbon being "processed" out of the fire. In this project, it was intended originally to determine the amount of unbound carbon indirectly on the basis of various material, or material and energy, balances. As discussed in Section 2.3, the quality of the data actually obtainable does not yet permit such a determination to be made to useful accuracy. In the follow-on series of experiments, sample exhaust gas streams will be passed through filters so that the unbound carbon production rate can be estimated by weighing.

2.2 Toxic Gas Measurement

In this laboratory, there is no capability for continuous monitoring of gas concentrations of interest for this project. Therefore, a sampling system was constructed. This system, shown in Fig. 10, is designed to collect four exhaust gas samples during the course of one test fire. Four 50 milliliter

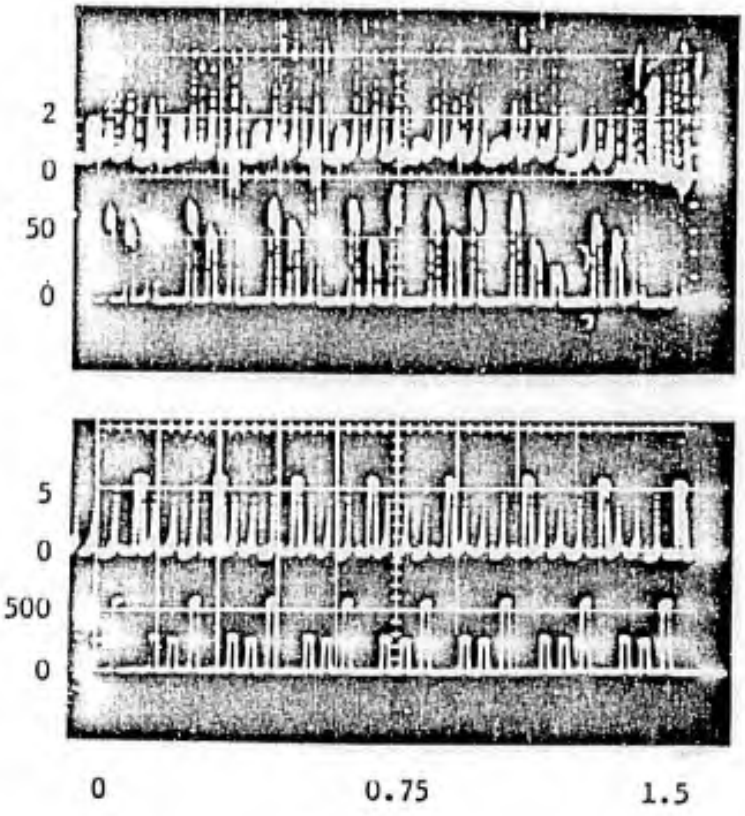


FIGURE 9 EXAMPLE SMOKE TRANSMISSION OSCILLOGRAPH TRACES

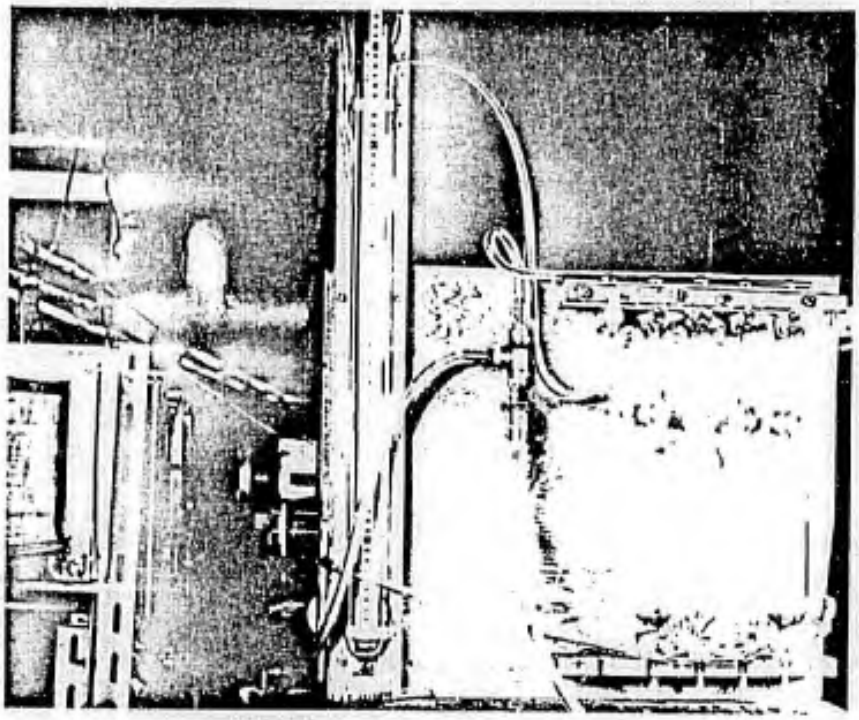
glass flasks are linked with the gas sampling port in the duct (Segment A, Fig. 1), a glass tube, Hg manometer, and vacuum line via a glass manifold.

The sample bottles are initially evacuated. At desired times during the course of a run, individual sample bottles are filled by opening a valve connecting them with the manifold and the exhaust system. The time resolution for this sampling process is certainly no worse than a few seconds. However, the volume of such extraneous gases is small enough to render this error unimportant.

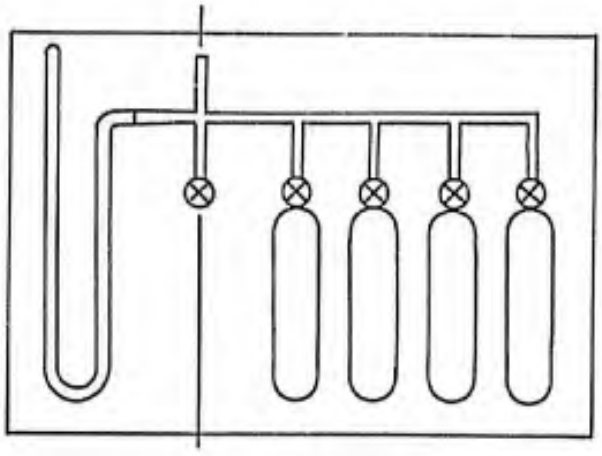
In the work to date, gas samples have been analyzed by gas chromatograph in the Industrial Hygiene Laboratory of the Environmental Health Department at the University of Washington. This laboratory has available a variety of columns and precision detectors, as well as other instruments, such as a mass spectrograph, as necessary. The mode of operation eventually adopted was for one of the Research Assistants on this project, Mr. Greg Cruz, to learn to operate the instruments needed for the desired analysis, and then to carry samples down to the Industrial Hygiene Laboratory where he performed the analysis himself. Operating this way, it has been possible to carry out these analyses on a no-cost basis, except for expendable materials consumed.

Before the arrangement with the Industrial Hygiene Laboratory was developed, a considerable amount of time was fruitlessly invested trying to perform gas analyses with a chromatograph with inadequate detector capability.

The toxic gas of current interest is CO. In addition to CO, concentrations of O_2 and CO_2 have also been determined, primarily with the intent to establish various material balances. In a few additional runs, concentrations of CH_4, C_2H_2, $n\text{-}C_4H_{10}$, and C_6H_6 have been obtained. In future work, it will be possible to study HCN, HCl, or other toxic gases of interest, as time permits.



To Gas Sampling Port,
Section A



To Vacuum Pump

FIGURE 10 GAS SAMPLING SYSTEM

2.3 System Equivalence Ratio and Material Balances

At the outset of this project, it was thought that most of the information of interest could be obtained on the basis of a relatively limited number of measurements for each run. In particular, if it is assumed that essentially all of the H atoms are oxidized to H_2O in the test fires, and that essentially all the C atoms go to CO_2, CO or solid particulate, then with measurements of the total flow rate out of the combustion chamber through the duct and of CO_2 and CO concentration there, only one further measurement is required to determine the total fuel consumption rate (or, equivalently, the rate of production of solid carbon). If the complete system is regarded as nearly adiabatic, then an energy balance based on a temperature measurement in the exhaust duct would in principle provide such determination. Alternatively, oxygen concentration measurement would provide the same determination. After a considerable amount of experimental repetition, it was finally concluded that neither of these approaches was sufficiently accurate. The relatively modest energy losses turn out to be large enough to completely hide the fraction of particulate carbon in an energy balance. Similarly, it turns out that oxygen concentration measurements good to nearly four signficant figures are required to obtain useful results.

An indication of this problem is given by Table 1. Here, attempts were made to determine the overall equivalence ratio ϕ of the fire chamber, regarded as a quasi-steady flow reactor. The precise definition of ϕ is the ratio of the actual fuel:air divided by the stoichiometric ratio of the fuel as consumed. In these experiments, the air flow rate is not directly controlled, but can be adjusted by varying the setting of the fan downstream of the exhaust duct (Fig. 1) and the ventilation configuration. Also, the rate of fuel consumption is not directly known, since this quantity adjust itself to ventilation and other conditions in the chamber. But the total flow rate out of a fire chamber is

determined by measurements in the exhaust duct. To get ϕ, an additional inference, tantamount to knowledge of the fuel consumption rate, is required.

In Table 1, three independent estimates are made for each of a series of gas samples taken on three runs on June 20 and June 26 (See Table 2, p. 26). The simplest method disregards solid carbon and CO entirely, and utilizes measured CO_2 concentration alone. This approach completely suppresses all knowledge of the particulate carbon concentration, but for the condition of interest it is probably a reasonably accurate way of determining ϕ for its own sake. The second method utilizes O_2 concentrations in addition to CO_2 and CO measurements to establish all of the desired balances. Application of this method yields estimates of ϕ consistently lower than estimates based on CO_2 alone. Even though the O_2 concentration measurements have been repeatedly checked against samples of known concentration, this discrepancy has still not been resolved. The third method, which is only a very rough approximation and provides only one estimate per run, is based on the observed time to fuel consumption and the known quantity of fuel in the pan.

All three methods give estimates of ϕ in the same general magnitude. However, these estimates correspond to adiabatic temperature differentials, relative to ambient, over twice as high as those measured in the exhaust duct. This suggests higher than anticipated heat losses in the system. It must be concluded at this stage that further attempts will have to be taken to establish material balances of the desired precision. A careful analysis of the conservation equations for this system suggests that the H_2O concentration in the exhaust duct is an excellent way to complete the material balances. In particular, the inferred particulate carbon concentration turns out not to be very sensitive to the H_2O concentration. Instruments for determining the H_2O concentration based on psychometric principles will be used in follow-on tests.

Date	Run No.	Sample No.	Approximation Method based on: CO_2 Alone	O_2, CO_2 and CO	Observed Fuel Consumption
June 20	1	1	0.199	0.115	0.13
		2	-	-	
		3	0.24	0.134	
		4	0.099	-	
June 20	2	1	0.199	0.14	0.24
		2	0.24	0.177	
		3	0.25	0.20	
		4	0.199	0.14	
June 26	1	1	0.168	0.105	0.13
		2	0.17	0.115	
		3	0.193	0.162	
		4	0.186	0.162	

TABLE 1 ESTIMATE OF OVERALL FIRE CHAMBER EQUIVALENCE RATIO

In addition, direct measurements of the majority of the particulate mass will be obtained by appropriate filter weighing.

Logically, the best method of all to resolve the difficulties referred to above is to directly determine the fuel consumption rate by, for example, weighing the pan. In the preceding work, this approach was deliberately avoided because eventually fuels not easily weighable will be used. For example, it would be desirable to hang electric cable bundles, install simulated furniture, or install simulated fuel-soaked piping insulation at arbitrary locations in the fire chamber. To maintain any experimental degree of freedom would effectively require weighing the entire chamber. This would introduce difficult precision requirements. In the immediate follow-on phase of the project, some direct fuel consumption measurements will be made by installation of suitable weight-sensitive transducers, for the purpose of validating and refining other methods outlined above.

3.0 Results - Smoke and Toxic Gas Production

A large number of runs have been carried out in the fire chamber. Most of these were devoted to attempts to establish material and energy balances, and to develop generally applicable but indirect methods of determining overall system equivalence ratio ϕ. Seven particular cases, in which fan size and ventilation parameters were varied, may be regarded as production runs. Results obtained for these cases are presented in this section.

Some of these cases were repeated in separate runs, as different measurements were made. Table 2 summarizes the conditions of these seven cases and relates them to particular runs.

Figures 11 through 16 present mass flow rates, exhaust duct temperature, and optical absorption data for these seven cases. The optical data as presented has a mass extinction coefficient γ for the exhaust gas stream. The units of γ are ft^2/lbm. To convert these units to cm^2 per gram, they should be multiplied by 2.05.

The mass flow rate $\dot{M}$ is determined by the fan setting and ventilation characteristics of the enclosure as disturbed by fire phenomena. The undisturbed value i apparent at time zero for each run. After ignition, $\dot{M}$ sometimes rises and sometimes falls, depending on fire characteristics. The reason for a rise in $\dot{M}$ is that the buoyancy of the flame gases enhances the driving pressure head. The reason for a fall is that the heating effect of the fire decreases the exhaust gas density, thereby requiring higher pressure heads for unit mass flow.

Gas analyses were carried out for four runs. These results are presented as Table 3.

Interpretation of these results is the subject of the following section.

Pan Size	Fuel Charge	Fan Setting	Runs
1' x 1'	Kerosene: 300 cc Gasoline: 50 cc	35	6-7-73 #1 6-20-73 #2
		40	6-7-73 #2
	Kerosene: 300 cc Gasoline: 100 cc	50	4-4-73 #1
	Kerosene: 300 cc Gasoline: 50 cc	100	6-7-73 #3 6-20-73 #1 6-26-73 #1
		100 w/ventilation @ 250 in^2 = 1.76 ft	6-7-73 #4
2' x 2'	Kerosene: 600 cc Gasoline: 100 cc	35	6-8-73 #1
		40	6-8-73 #2
		100	6-8-73 #3

TABLE 2 SUMMARY OF SMOKE AND TOXIC GAS PRODUCTION RUNS

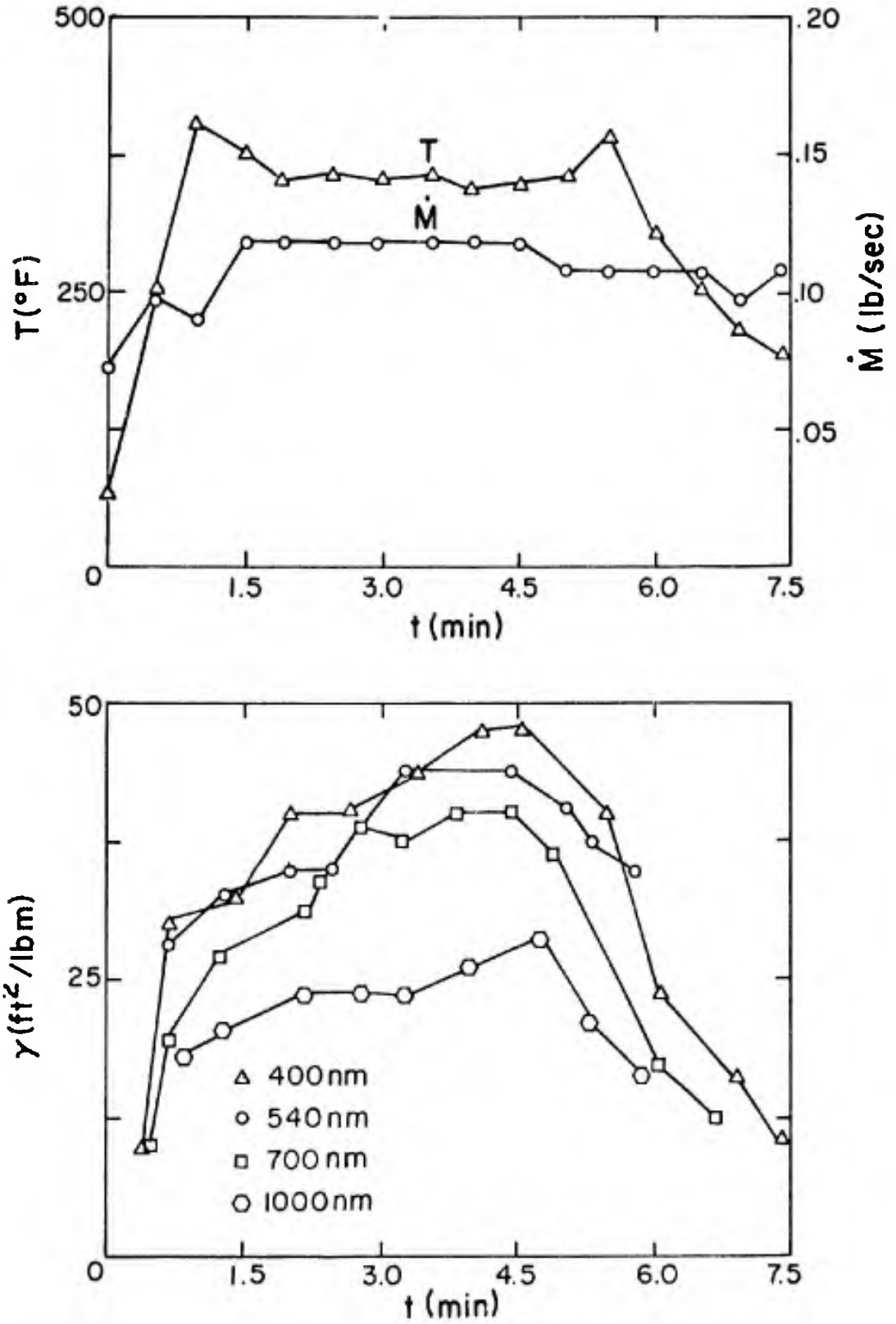


FIGURE 11 FIRE CHAMBER AND SMOKE DATA - 1x1 ft. PAN FIRE; FAN SETTING 35; NO VENTILATION PANELS REMOVED

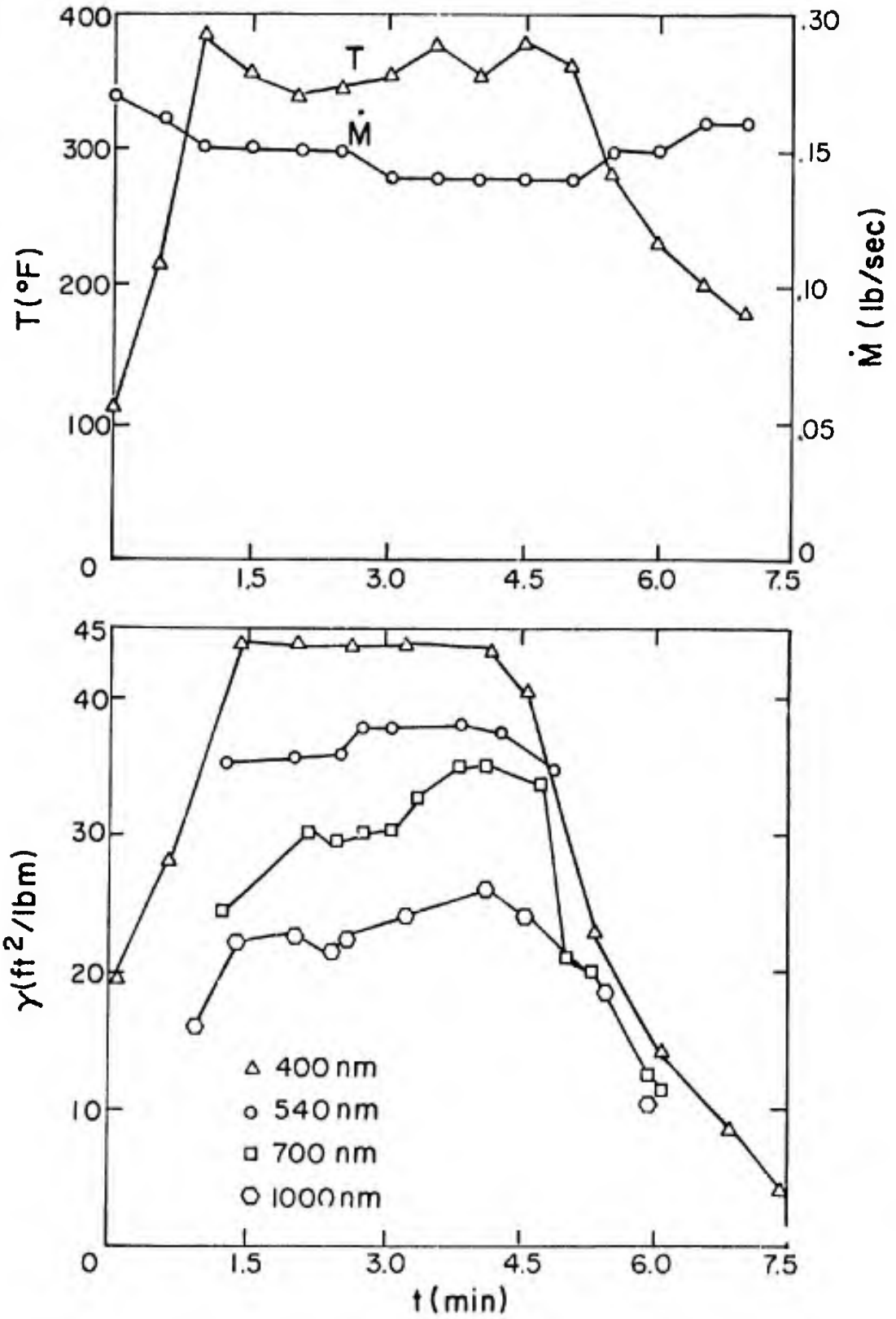


FIGURE 12 FIRE CHAMBER AND SMOKE DATA - 1x1 ft. PAN FIRE; FAN SETTING 40; NO VENTILATION PANELS REMOVED

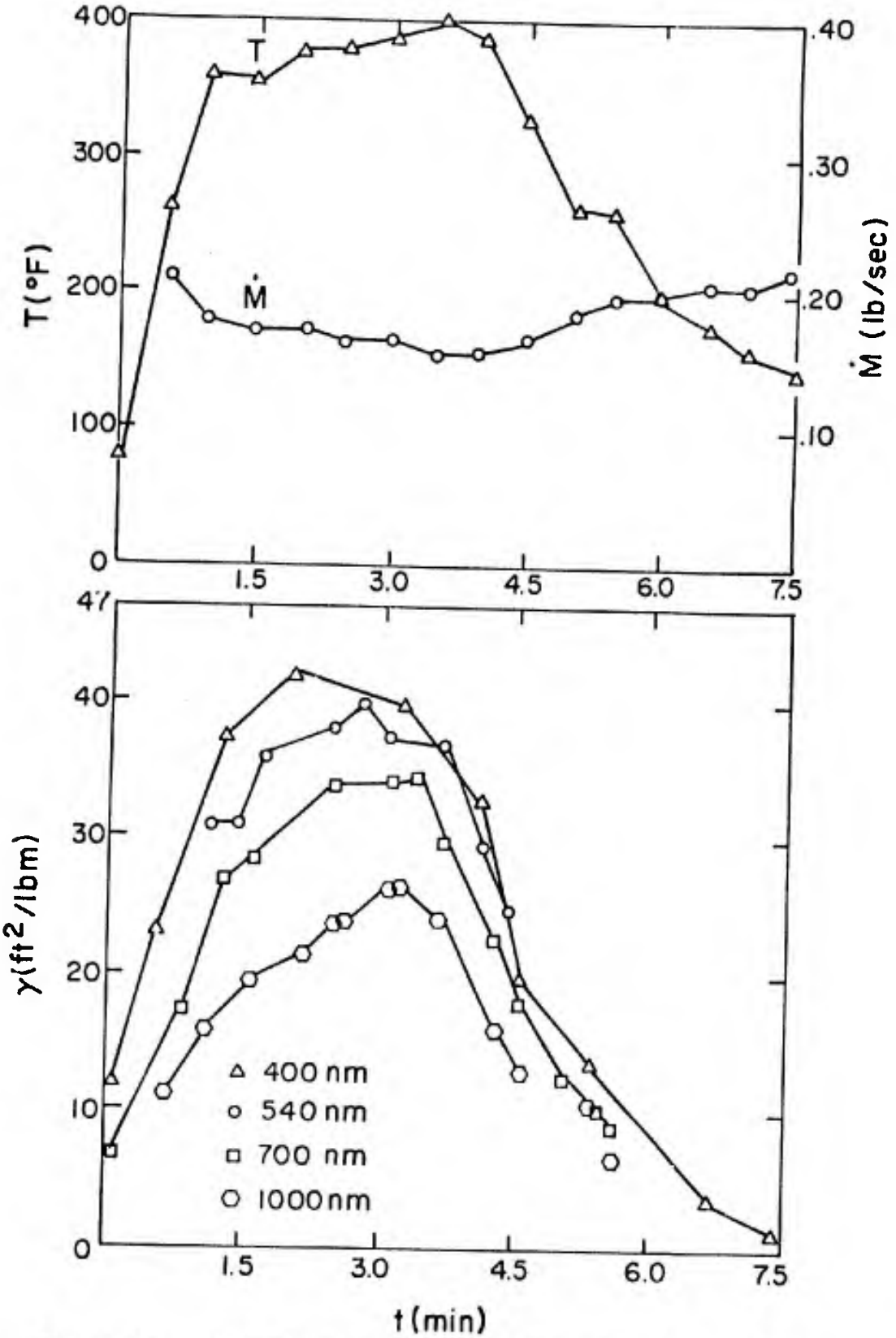


FIGURE 13 FIRE CHAMBER AND SMOKE DATA - 1x1 ft. PAN FIRE; FAN SETTING 100; NO VENTILATION PANELS REMOVED

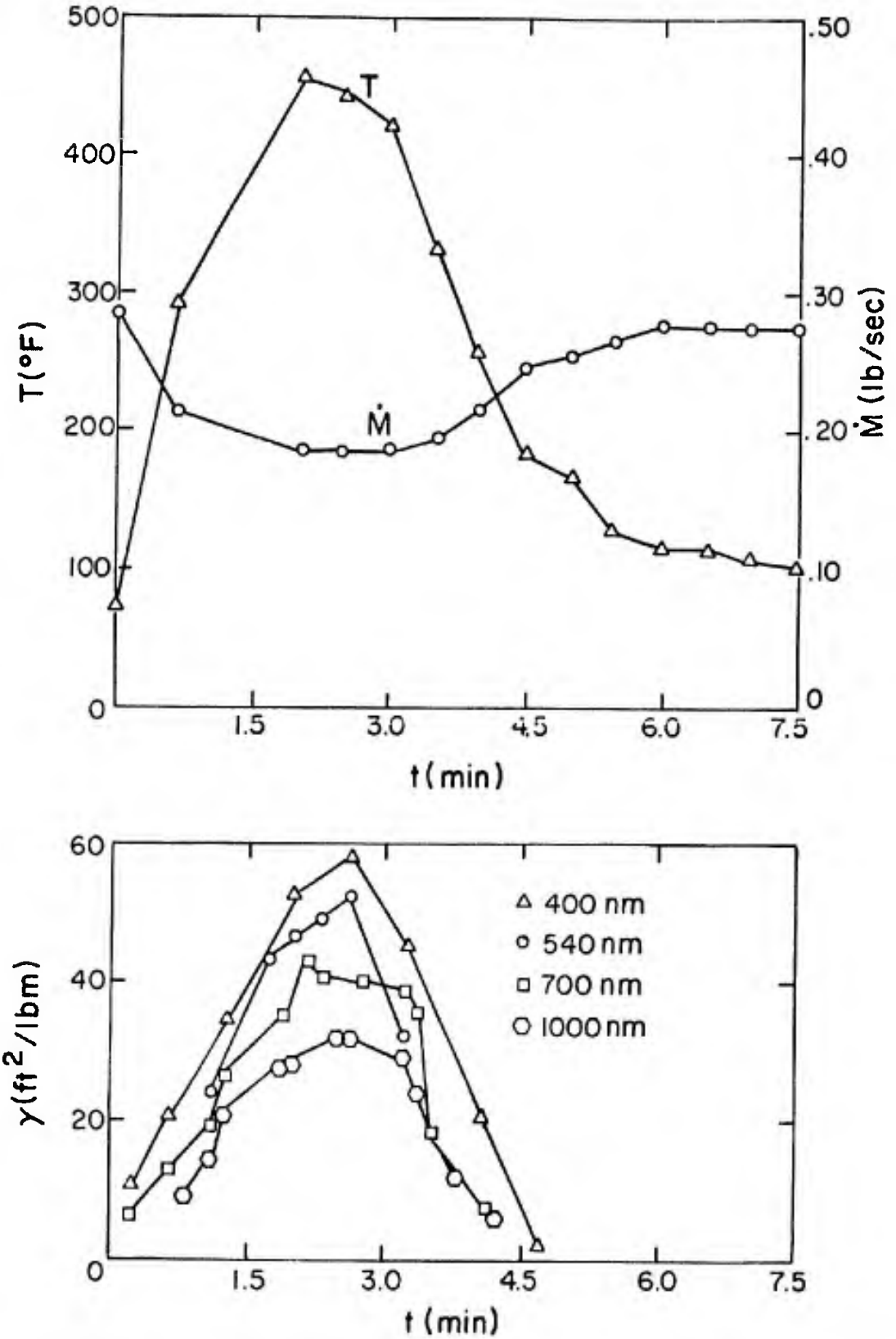
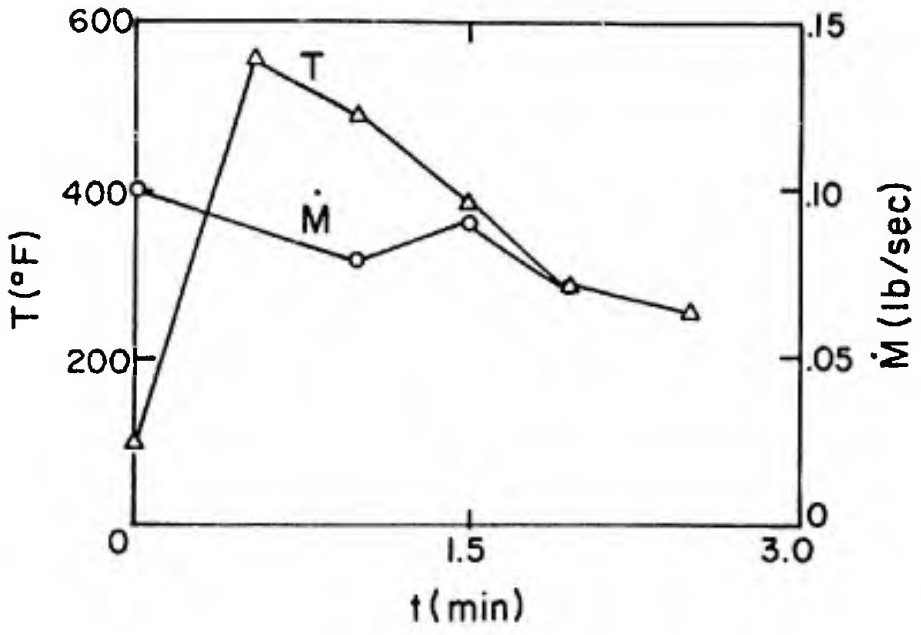


FIGURE 14 FIRE CHAMBER AND SMOKE DATA - 1x1 ft. PAN FIRE; PAN SETTING 100; 1.76 ft.^{2} (1640 cm^2) VENT PANEL OPEN



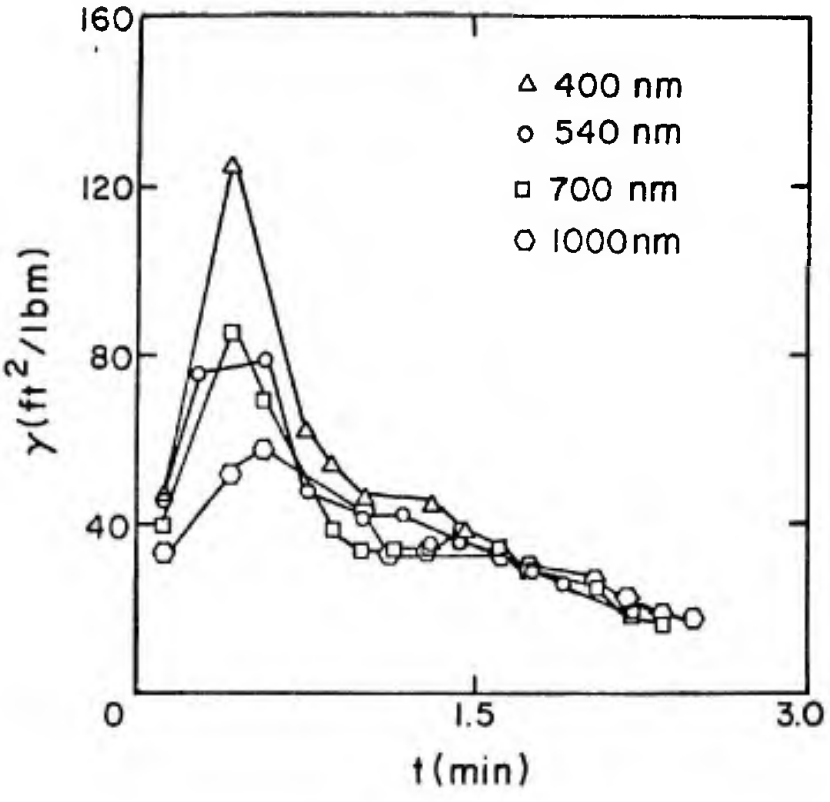


FIGURE 15 FIRE CHAMBER AND SMOKE DATA - 2x2 ft. PAN FIRE; FAN SETTING 35; NO VENTILATION PANELS REMOVED

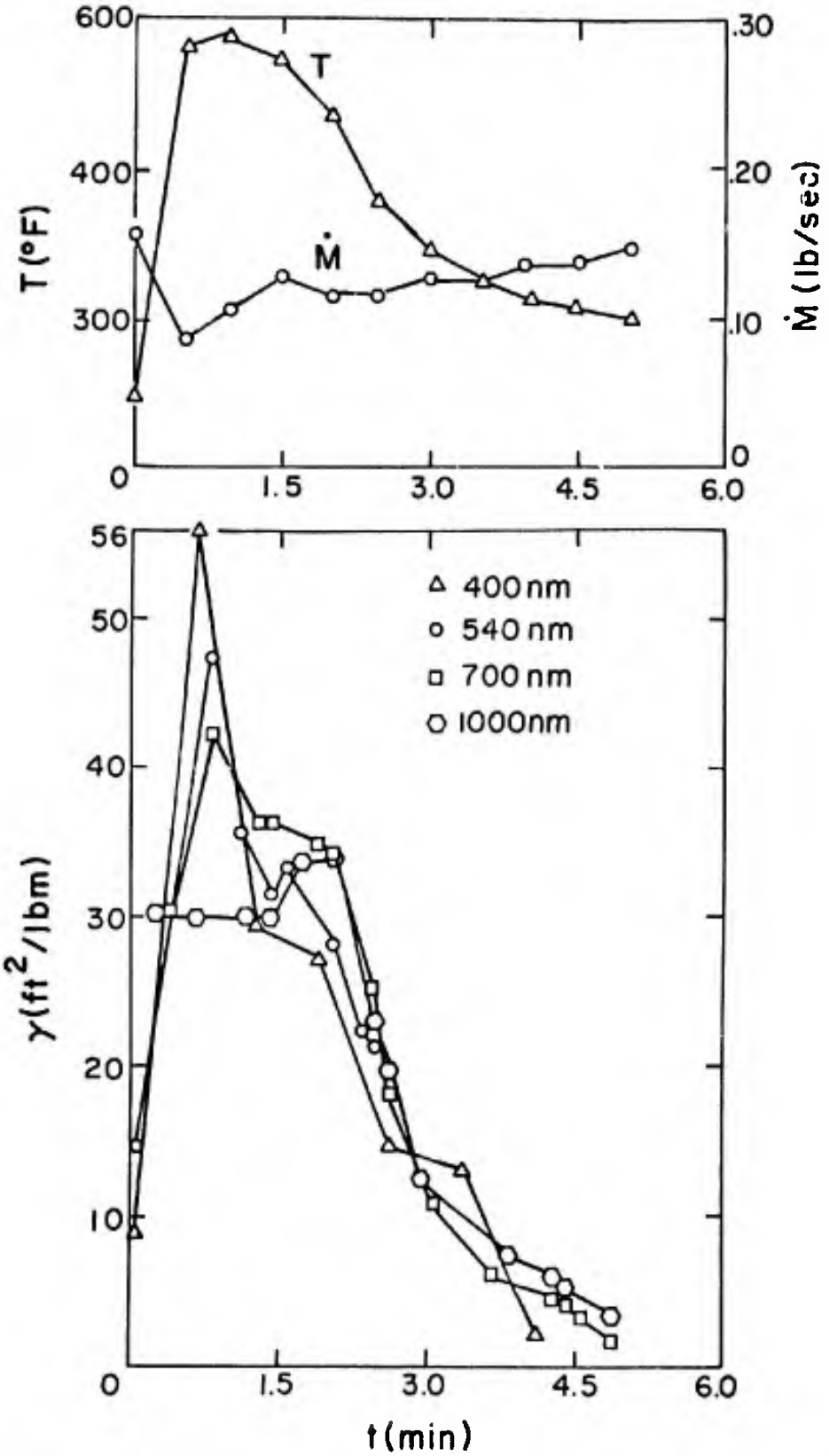
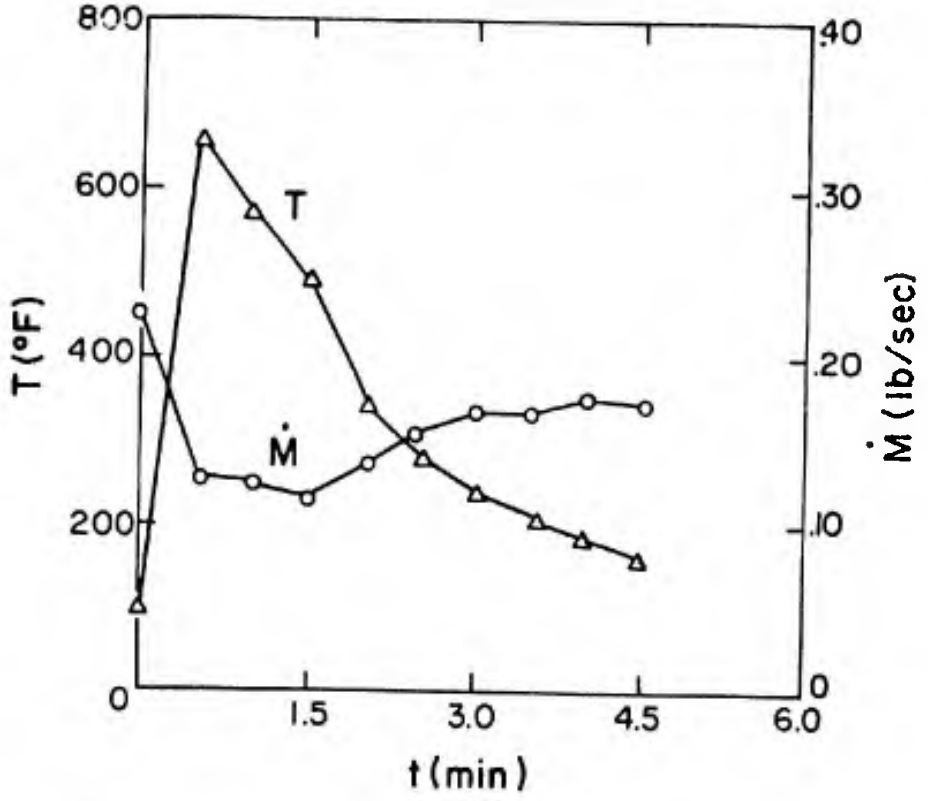


FIGURE 16 FIRE CHAMBER AND SMOKE DATA - 2x2 ft. PAN FIRE; FAN SETTING 50; NO VENTILATION PANELS REMOVED



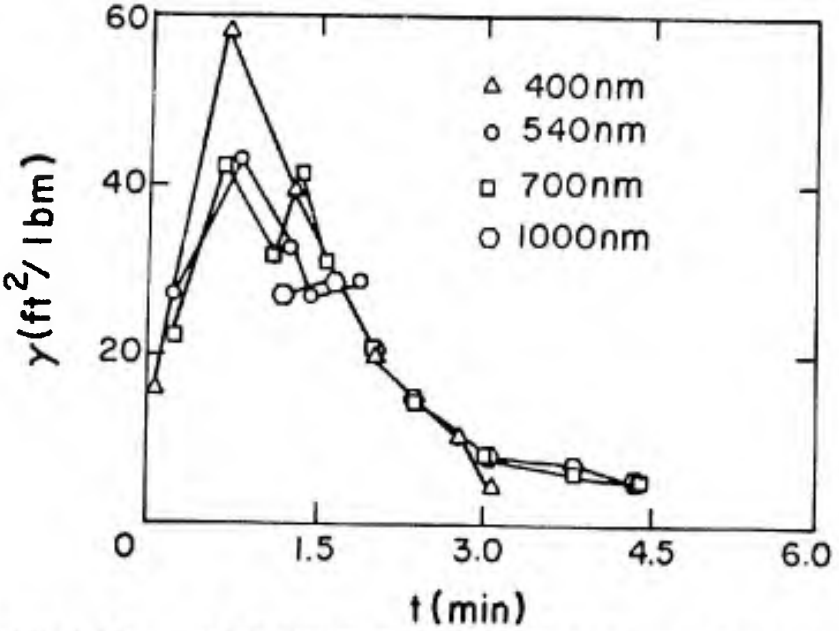


FIGURE 17 FIRE CHAMBER AND SMOKE DATA - 2x2 ft. PAN FIRE; FAN SETTING 100; NO VENTILATION PANELS REMOVED

Date	Run No.	Sample No.	O_2	CO	CO_2
April 4*	1	1	18.3	0.045	0.72
		2	18.2	0.059	0.86
		3	17.8	0.067	0.96
		4	18.5	0.055	0.76
June 20	1	1	18.6	0.041	2.8
		2			
		3	18.2	0.040	3.4
		4		0.020	1.4
June 20	2	1	18.4	0.058	2.8
		2	17.3	0.067	3.4
		3	16.8	0.071	3.5
		4	18.0	0.049	2.8
June 26	1	1	18.8	0.041	2.35
		2	18.6	0.038	2.4
		3	17.6	0.040	2.7
		4	17.6	0.041	2.6

* In addition to the above analysis for the run of April 4 the following data was obtained:

Sample No.	Methane	Acetylene	N-butane	Benzene
		PPM		
1	25	24	36	4
2	20	12	2	2
3	39	45	11	5
4	30	36	2	4

TABLE 3 GAS ANALYSIS RESULTS

4.0 Discussion - Smoke and Toxic Gas Production

In the data so far collected, four general features are noteworthy. First, a relatively clear pattern of wavelength dependence is revealed. During the active burning phase of each run, that is until the exhaust gas temperature begins to fall rapidly from its peak value, the extinction coefficient γ tends to decline with increasing wavelength γ . No attempt has been made to carry out a statistical analysis to quantify this dependence, but its general magnitude is inverse linear. In the die-down phase of each fire, the wavelength dependence of γ tends to disappear. It is known[3] that, in the Rayleigh limit wherein particle size is an order of magnitude or more less than wavelength, $\gamma \propto \lambda^{-4}$. At the other limit, wherein the particle diameter is on the same order as or greater than the wavelength, γ is approximately independent of λ. The latter limit seems to apply to the die-down phase. In the intense burning phase, apparently neither of the two limits is applicable. This suggests that the size of the particles responsible for most of the scattering is somewhat lower than 400 nm but not by as much as an order of magnitude. This is consistent with other evidence regarding the size of particulate matter in flames[6]. By making suitable assumptions - a suitable mean complex index of refraction, spherical particle geometry(whereas the actual scattering particles are almost certainly geometrically complex aggregates of smaller particles) and predominant single scattering - it would be possible to deduce a particle number density versus wavelength distribution function of four or less parameters from this data.* This is certainly a worthwhile exercise, which will be eventually undertaken. However, even without further analysis, this wavelength dependent transmission data constitutes

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* Given comprehensive wavelength dependent data, the particle size distribution function can be obtained in detail by solution of an integral equation.[7]

a useful smoke characterization.

On the basis of data so far available, no clear biasing of the wavelength transmission dependence is evident with respect to variation of pan size or ventilation parameters. There is a slight suggestion (Figs. 13 and 14) that for the 1×1 ft pan the wavelength dependence tends to persist somewhat into the die-down phase for relatively well-ventilated conditions. However, a better data base is required to establish this.

The second general feature is the test of the hypothesis that smoke production, as characterized by an extinction coefficient per unit fuel consumed, is independent of burning conditions. In this case the variable of interest is γ/ϕ, where γ is the equivalence ratio discussed in Section 2.3. The quantity γ/ϕ can be interpreted as an extinction coefficient in units of area/mass stoichiometric combustion products (whereas γ alone is an extinction coefficient with units of area/mass stoichiometric combustion products plus mass excess air). According to the hypothesis, $\gamma/\phi \equiv$ constant for any single fuel composition. As indicated in Section 2.3, it has not been possible to establish the ϕ as well as is needed for a quantitative test of the hypothesis. However, the data available suggests that the general order of magnitude of γ/ϕ is 100 ft sq/lbm and that this quantity increases significantly with overall fire chamber burning rate.

The third general observation regards the coupling between the fire chamber mass throughput $\dot{M}$ and burning conditions. A nominal value of $\dot{M}$ is determined by the fan setting and the ventilation configuration, in the absence of the fire itself. For the 1×1 ft pan at the lowest fan setting (Fig. 11), $\dot{M}$ is increased by the fire. For all other cases, $\dot{M}$ is decreased by the fire. Apparently there is a competition between the buoyant effect of the fire and the

increase of pressure head required because of the increased volumetric flow due to combustion heating.

The data obtained sofar merely point up the sensitivity of $\dot{M}$ to ventilation parameters and fuel consumption rate. However, it is very important to bear in mind that this experiment is hydrodynamically a simple series system with $\dot{M}$ dominated by factors other than the fire itself. But in a real ship, in which the flow path is complex with many parallel routes, it is anticipated that the type of coupling indicated here could be very much more pronounced. Indeed, in a parallel flow system, it is possible to envisage an order of magnitude reduction in throughput due to combustion heating. This could result in smoke accumulations in some enclosures much more persistent than anticipated on the basis of the cold flow performance characteristics of the ship's ventilation system.

The final general observation regards the CO concentration. As indicated in Table 3, these concentrations are persistently in the 400-700 PPM range for the 1×1 foot pan. These concentrations, or particularly, the CO/CO_2 ratios, are somewhat lower than originally anticipated but are consistent with some other reported experience[8]. It is anticipated that the CO/CO_2 ratio will be much larger for some different fuels.

4.1 Work Plan for 1973-74 Follow-on

Principal follow-on activities in the area of smoke and toxic gas production are described in this section. Approximately 100 production runs, in which exhaust flow characteristization, fuel burning rate, smoke characteristics and gas analyses are obtained, are planned to provide a meaningful data base.

At least a third of the anticipated runs will continue to use kerosene as a primary fuel. In these runs, a wider range of ventilation conditions and fuelbed geometry will be explored. The specific matrix of tests to be carried out will be defined in consultation with project sponsors.

A considerable quantity of surplus electrical cable has been procured from the Puget Sound Naval Shipyard at Bremerton, Washington. Both armored and non-armored cable are on hand. Simulated cable bundles will be constructed and attached to the walls of the fire chamber and burnt in conjunction with kerosene pans below. In this case, additional chemical analysis will be required since the cable insulation assembly presumably contains a number of halogenic compounds.

5.0 Fire Suppression Experiments

An important secondary objective of this project was the development of experimental capability for suppression modeling. The chamber has been equipped to carry out a wide variety of controlled suppression experiments, and a series of pilot runs have been carried out.

Fig. 18 illustrates the general geometry of the suppression system. The main flow pipe is mounted on two support pipes. The elevation of the support pipes and the horizontal location of the main flow pipe on the support pipe can easily be changed, although new connecting lines must be formed for each configuration. This is a relatively minor task. The main flow pipe has a hole in the center for a nozzle. It can easily be replaced by a differently located single nozzle or multiple nozzles.

The system has been arranged so that controllable flow rates of the water, CO_2 or Purple K entrained in any desired gas (currently CO_2) are applied for time increments precisely controlled by a solenoid valve. The flow rates of water and CO_2 are determined from the preadjusted supply pressure. The relationship between supply pressure and flow rate has been established by direct calibration.

A considerable amount of preliminary experimentation was required to develop a satisfactory Purple K injection scheme. The method finally adopted was to store the powder in a cylindrical container outside the fire chamber, and then to blow gas upwards through the powder, thereby entraining a suitable amount, and thence through a line from the top of the cylinder into the suppression system. What is observed currently is a combination of Purple K and CO_2 suppression effects. But it is no problem at all to switch to other inert gases, such as N_2 or even to air.

Results for 18 runs are summarized in Table 4. All of these runs were in

the 1×1 ft pan with a 300 cc kerosene and 50 cc gasoline fuel loading.

It is inappropriate at this time to attempt a meaningful physical interpretation of these results. The project is now prepared to rapidly acquire an adequate empirical data base for testing any suppression criteria of interest (such as Williams' Damkohler number criterion)[1,9]. Some of these runs will be repeated in a scaled-down version of the fire chamber. At present, a scaling factor of 2 is anticipated.

On the basis of purely theoretical considerations, it has not been possible to derive confident scaling rules for fire suppression. One of the main reasons for developing a reasonably wide empirical data base is to gain some insight on which parameters are most important. Hopefully, this will suggest approximate, semi-empirical rules that can be applied to the scaling problem.

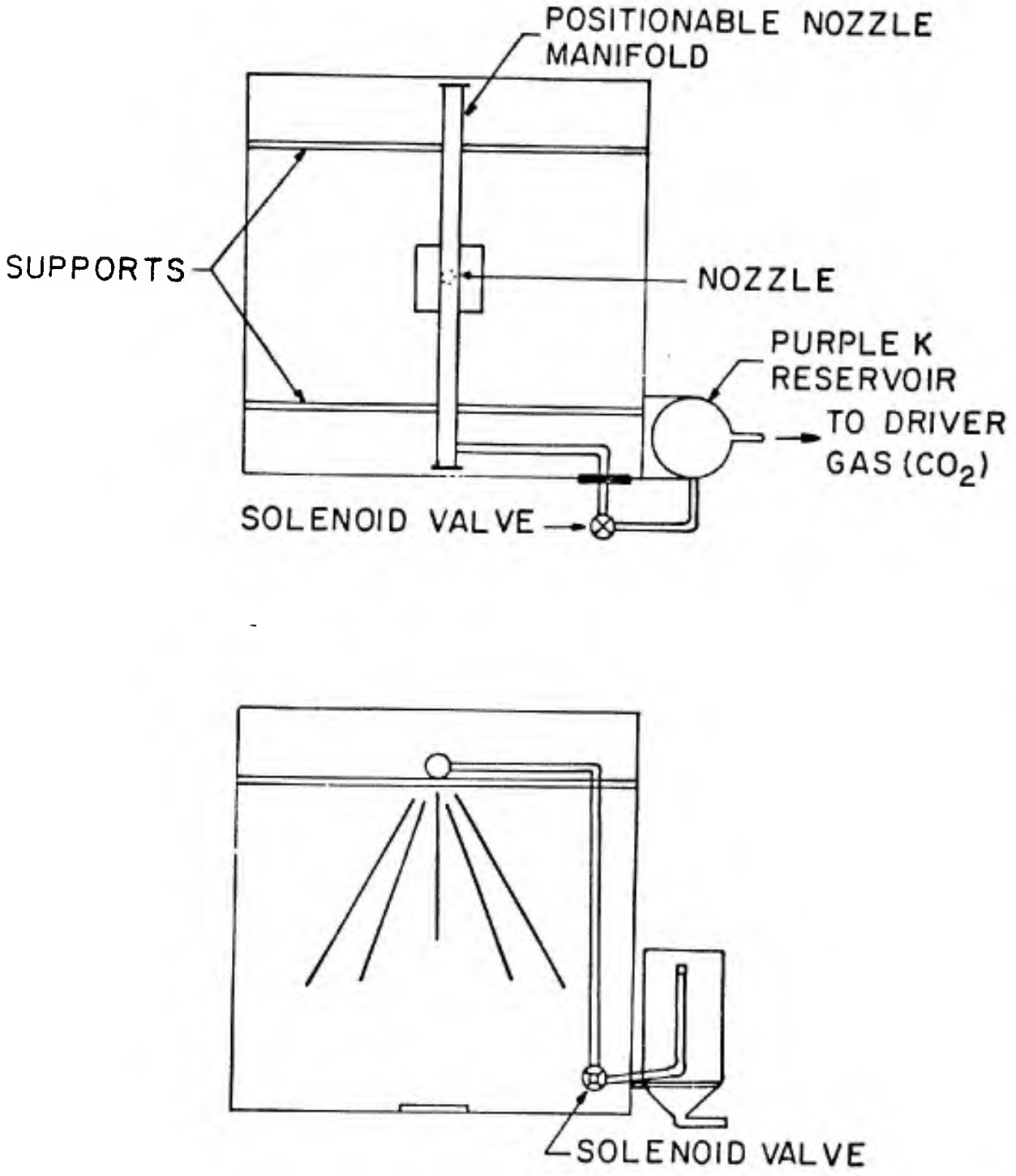

FIGURE 18 FIRE SUPPRESSION SYSTEM
TOP VIEW

Fan Setting	Agent	Pressure (psig)	Time (sec)	Comments
100	Water	20	270	Water on 60 sec after ignition. Chamber pressure increases when valve is open. Flames tend to spread away from pan. After run, pan is half-covered with water and sand is accumulated on opposite side.
100	Water	64	12	Little sparks form when fire starts. Flame height lowers at once when valve is opened. All through test, a strong wind seems to blow on top of fire. No sand in pan center after test.
100	Water	50	17	Same as previous case.
100	Water	30	Not Recorded	Fire stays steady and doesn't spread when valve is opened. Chamber pressure increase less than at higher pressures. Fire extinguished in an even manner.
100	CO_2	15	Not Recorded	Flame spreads out a little when valve is opened. After 40 sec, pressure raised to 20 psig for 30 sec before fire extinguished. Sand half-dry following run.
100	CO_2	30	13	Same as previous case except sand is still hot following run.
100	CO_2	20	20	Flame seems to be blown by strong wind on top. Does not burn straight.
100	CO_2	15	27	Same as previous case except for less fire spreading.
100	Purple K & CO_2	40	-	Purple K valve not fully opened. Test failed.
100	Purple K & CO_2	10	-	Upon valve opening, flame lowers a little but does not extinguish. As pressure is raised to 15 psig, flame spreads away from pan and extinguishes.

TABLE 4 SUMMARY OF FIRE SUPPRESSION PILOT RUN DATA

Fan Setting	Agent	Pressure (psig)	Time (sec)	Comments
100	Purple K & CO_2	12	-	Again strong wind seems to blow on top of flame. No extinguishment. After increase to 15 psig, still not extinguishment. Extinguishment at 18 psig. At 18 psig, powder is clearly observable in exhaust smoke.
35	CO_2	30	5	Flame again seems strongly blown at top.
35	CO_2	20	7	Increase in chamber pressure. Flame doesn't spread as much as in preceding case.
35	CO_2	15	38	Very little disturbance of flame.
35	Water	20	480	Flame quite uneven when valve is off. Very little fire at pan center. Water not very effective this run. 11.26 gallons used.
35	Water	30	130	Fire set away from pan as soon as valve opened. Non-uniform burning. 3.45 gallons used.
100	Water	50	17	Same as above. 1.34 gallons used. Some fuel found on floor following test.
100	Water	60	10	Large chamber pressure increase. 0.67 gallons water used.

TABLE 4 SUMMARY OF FIRE SUPPRESSION PILOT RUN DATA (Continued)

6.0 Concluding Remarks

An experimental system has been developed for the investigation of smoke and toxic gas generation, and fire suppression, under conditions typical of enclosed shipboard fires. Although some suggestive results have been obtained, considerably more data will be required before clear interpretation, in either practical or fundamental scientific terms, can be made.

In general, progress on this project is not limited by either cost or time requirements for obtaining and controlling the phenomena. Rather, the limiting factor is ability to obtain chemical data and meaningful smoke characterization. It is believed that capability to perform these functions has now been improved to the point where the rate of data acquisition can markedly increase.

In designing the experimental system, and generally in the development of ideas, the Principal Investigator has endeavored to keep real shipboard fire problems in mind. Toward this end the visit, accompanied by F. A. Williams of the University of California, San Diego, to the aircraft carrier Constellation in San Diego on September 14, 1972 was of great benefit. Not only did this visit lend considerable insight into the true nature of aircraft carrier fire problems, but also more sharply delineated that ship's present fire-fighting capabilities relative to potential benefits of research. It was clear from the visit that the engineering officers on the Constellation were knowledgable of their fire problems and assigned high priority to fire-fighting equipment, tactics and strategy, and training.

As a part of this project, the Principal Investigator has been able to collaborate on a variety of fire research activities with F. A. Williams, and with A. S. Gordon of the Naval Weapons Center at China Lake, California and

Ray Alger of the Naval Ordnance Laboratory (stationed at Stanford Research Institute, Menlo Park, California). These activities have provided valuable feedback to the experimental activities described above in this report and certainly have contributed to the probability that the results of this research will be quickly and successfully applied. Last, but not least, this collaborative effort has helped in a number of ways to advance the state of knowledge regarding fundamental fire phenomena.

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APPENDIX

WSCI 72-35

MODELING HYPOTHESES FOR SMOKE PRODUCTION IN ENCLOSED FIRES

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ABSTRACT

A formalism for predicting smoke production by a prototype fire on the basis of suitable model fire measurements is set forth. The underlying assumptions are: 1) the existence of an overall rate equation for the local production rate dz/dt of a smoke constituent whose concentration is z, as a function of the local value of z itself and of the local gross fire state, that is the temperature and gross fuel, air and products concentrations; 2) the fields of the gross fire state variables are essentially independent of chemistry (that is, they are diffusion controlled), and through mass and heat transfer similarity are all expressible in terms of the field of the absolute equivalence ratio ϕ; 3) for purposes of smoke production every fire has a characteristic ϕ history experienced by burning fuel elements; and 4) the z and ϕ dependence in the ratio fraction is separable.

The potential application of the smoke modeling formalism to scaling problems of considerable complexity, in which model and prototype ϕ histories are piecewise similar, is described. However, a number of practical difficulties must be overcome and some knowledge gaps filled before any but the simplest modeling experiments will be of value. In this spirit, some smoke production modeling hypotheses which should admit to experimental test are indicated.

INTRODUCTION

Smoke produced by unwanted fires creates several serious problems. To begin with, smoke has adverse physiological effects on individuals. These range from mere discomfort to death. The real or perceived need to avoid them may significantly impede fire fighting efforts. Furthermore, smoke impairs visibility, thereby indirectly hindering fire fighting and contributing to difficulty of escape. Finally, the presence of smoke constitutes diagnostic information -- the amount and type of smoke generated tells people or various detection systems something about the location and severity of a fire.[1]* Often this information is incompletely or erroneously interpreted.

In designing large systems, such as buildings or ships, or developing fire protection strategies for such systems, it is highly desirable to be able to predict the smoke production characteristics for various assumed fire situations. A completely empirical approach to generating such information would require a large number of full scale test fires faithfully representing

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* Raised parenthesized numerals denote references at the end of this paper.

the situations of interest. Such an approach is clearly unacceptable, for reasons both of cost and time consumption. In practice this difficulty is circumvented by characterizing the smoke producing potentials of the materials present on the basis of small scale laboratory experiments (e.g., Refs. 2,3). The knowledge of overall fire behavior is used to predict burning rates, and thence smoke production rates and concentrations. Christian and Waterman[4] have recently discussed the limitations of small scale tests as a basis for smoke hazard prediction.

The weakness of any approach which relies directly on small scale test results is that it neglects the dependence of smoke production potential on any variables other than the identity of the fuel. This is most reasonable in cases where the smoke constituents of interest are equilibrium combustion products, such as metallic oxide particles. But many types of smoke, and probably the great majority of those of practical interest, are essentially non-equilibrium combustion products. The extent of production of such smoke fires may depend on the conditions for chemical reaction presented by the fire of interest. These conditions are certainly characterized by a time scale, and presumably also by temperature and fuel or oxygen concentration. These in turn must depend on such overall fire characteristics as length scale, extent and patterns of ventilation, and perhaps fuel bed arrangement.

This paper is a preliminary step toward dealing with the dependence of smoke concentration and smoke production rates on parameters other than fuel identity. The long range objective is to determine the smoking characteristics of a fire in situations of practical interest -- called the prototype -- on the the basis of model tests. In this sense, the model test differs from the prototype fire in that some elements of reality have been abandoned for purposes of economy or generality. Scale modeling is a special case of this generalized modeling concept. However, in dealing with enclosed fires especially, other modeling steps such as geometric simplification, adjustment of ventilation or replacement of fuels, are also of interest.

The ideas set forth in this paper were developed preliminary to a series of model fire experiments designed to elucidate the dependence of smoke production on fire variables other than fuel identity. The basic approach adopted entails some extreme simplifications which, hopefully, will provide a basis for interpreting our test data.

Here we begin by setting forth a general modeling formalism whose derivation is made possible by some fundamental assumptions, and which contain unknown parameters to be adjusted in the light of experimental information. The modeling formalism is set forth in far greater generality than can be utilized in terms of immediately anticipated experimental data. But if the underlying assumptions prove to be sufficiently close approximations to reality, then this formalism should provide the foundation for a great variety of further research.

GENERAL MODELING FORMALISM

In this development, z stands for the concentration of some smoke constituent in a model experiment, and Z represents the concentration of a smoke

constituent of interest in a prototype situation.* In general, these two constituents need not be the same. All that is necessary is that their overall production and consumption kinetics be similar in a sense to be described below.

Our first assumption is that the local smoke production rate in the model, dz/dt, may be satisfactorily approximated as a function of local values of its own concentration z and such gross fire variables as temperature and oxygen and fuel vapor concentration. An analogous assumption applies to the description of dZ/dt. Examples of such overall expressions are those summarized for after-flame CO consumption by Singh and Sawyer[5] and for soot oxidation by Wright[6].

In most unwanted fire situations -- that is, situations with reasonable thermal boundary conditions and fuel initially unmixed with air -- the distributions in time and space of these gross fire variables is essentially independent of chemical rates. The characteristic chemical times for overall energy conversion (and overall fuel consumption) are much less than the characteristic diffusion time. Furthermore, because of heat and mass transfer similarity, there is a connection between the temperature and the gross fuel, air and production fractions. In this work, all of these quantities will be assumed expressible as functions of local absolute equivalence ratio ϕ. At any point in time and space, the value of ϕ is here defined as the ratio of what the equivalence ratio would be if the mixture there were decomposed into unburnt fuel and ambient air. The "fuel" may be a mixture and the "air" may contain diluents. Where $\phi > 1$, the air fraction Y^A is essentially zero, and the gas composition consists roughly of a fraction Y^F of fuel and a fraction $1 - Y^F$ of combustion "products." Where $\phi < 1$, then the fuel fraction is essentially zero, and the mixture consists of air and "products." The fuel and air fractions and the dimensionless temperature may be expressed in terms of

$$\theta = \frac{T - T_\infty}{T_{af} - T_\infty},$$

$$\theta \simeq 1 - Y^F \simeq (\lambda+1)/(\lambda+\phi) \quad [\phi \geq 1], \tag{1}$$

$$\theta \simeq 1 - Y^A \simeq (\lambda+1)\phi/(\lambda+\phi) \quad [\phi \leq 1]$$

Here T_∞ and T_{af} are respectively the ambient temperature and the adiabatic flame temperature of stoichiometric fuel and air, and λ is the stoichiometric air/fuel ratio. As used above, the terms "fuel," "air" and "products" are chemically imprecise. For example, the heated fuel vapors will undergo pyrolysis

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* For purposes of this discussion, z or Z could also represent concentration of non-equilibrium gas products, such as carbon monoxide CO.

reactions which are extremely complicated in detail. The fundamental premise enunciated above amounts to the neglect of such details insofar as they contribute to the overall thermal and chemical environment for smoke production, and cannot be characterized once and for all as properties of the fuel being burned.

Our fundamental assumption may thus be expressed

$$dz/dt = g\ (z,\ \phi)$$

$$dZ/dt = C\ (Z;\ \phi) \qquad (2)$$

The functions g and G are assumed to be fully characterized by the identity of the burning fuel. The smoke constituents z and Z will be said to be kinetically similar if the functions g and G are the same within a multiplicative constant; i.e., for identical arguments

$$G = s\ g \qquad (3)$$

Having gone this far, it is a short step further to assume that the z (or Z) and ϕ dependence are separable. Thus

$$dz/dt = f(z)\ F\ (\phi)$$

$$dZ/dt = s\ f(z)\ F\ (\phi) \qquad (4)$$

for kinetically similar smoke constituents. The usual form of the function f in overall kinetic expressions is the reaction order factor, e.g.,

$$f(z) = z^m\ .$$

The function F is normally much more complicated, since this contains the temperature dependence.

Fortunately the function F does not enter into the modeling formalism provided that the equivalence ratio histories for the model and the prototype are similar. By an equivalence ratio history we mean the variations of ϕ with time t experienced by a typical particle of fuel vapor as it passes from its source through the fire. Presumably, ϕ decreases monotonically with t. It is admitted that there are actually many simultaneous equivalence ratio histories in any one fire. The idea here is that, for purposes of smoke

production, a fire may be characterized by a single "typical" equivalence time history. Logically this is entirely analogous to the characterization of a combustor as a pollutant generator by "typical" or "mean" (primary and secondary zone) residence times. Now the model and prototype equivalence ratio histories will be said to be similar if they are identical except for a constant time scaling ratio; i.e.,

$$\phi = \phi(t) \qquad \text{[model]}$$

$$\phi = \phi(t/\gamma) \qquad \text{[prototype]} \tag{5}$$

Fires which are well scaled in the sense that the fields of temperature, overall air and fuel concentration and flow velocities are the same except for length and time scaling factors have similar equivalence ratio histories in this sense. This concept of equivalence ratio history can be generalized to one of stepwise similarity. A model fire and a prototype fire will be said to have stepwise similar equivalence ratio histories if the full range of equivalence ratios encompassed (usually ranging from some very large number to zero) can be broken up into a sequence of equivalence ratio intervals such that for each interval, say $\phi_a > \phi > \phi_b$, a value of the time scaling ratio γ can be found to satisfy Equation 5. As an example, fires might have similar equivalence ratio histories with one time scaling ratio in the fuel-rich regions ($\phi > 1$) and a different value in excess air region ($\phi < 1$).

We now address ourselves to the following mathematical problem. Suppose at the beginning of the equivalence ratio interval $\phi_b > \phi > \phi_a$, for which model and prototype equivalence ratio histories are similar with time scaling ratio γ and initial values of concentration z_i and Z_i of kinetically similar smoke constituents are known. Suppose also that the model smoke concentration at the end of the interval, z_f, is also known. Then we wish to determine the final value of the prototype smoke concentration Z_f.

With no loss of generality we take time t=0 at $\phi = \phi_a$. We change dependent variables

$$y(z) = \int_{z_i}^{z} \frac{dz}{f(z)}, \qquad Y(Z) = \int_{Z_i}^{Z} \frac{dZ}{s\gamma f(Z)} \tag{6}$$

and prototype independent variable

$$\tau = t/\gamma . \tag{7}$$

Then the histories of y and Y are governed by identical differential equations with identical initial conditions.

$$dy/dt = F(\phi(t)) \qquad y=0 \ @ \ t=0$$

$$dY/d\tau = F(\phi(\tau)) \qquad Y=0 \ @ \ \tau=0.$$

Thus at the end of the interval when $\phi = \phi_b$, y and Y must have identical values. Letting Y^{-1} be in the inverse of the function Y(Z), we have then

$$Z_f = Y^{-1}\,[y(z_f)]\ . \tag{8}$$

For example, suppose $f(z) = z^m$, with $m \neq 1$,

$$y(z) = \frac{z^{1-m} - z_i^{1-m}}{1-m}$$

$$Y(Z) = \frac{Z^{1-m} - Z_i^{1-m}}{\gamma s(1-m)}$$

$$Y^{-1} = Z(Y) = [\gamma s(1-m)Y + Z_i^{1-m}]^{\frac{1}{1-m}} \tag{9}$$

If the initial values z_i and Z_i are zero, then m must be restricted to the range $m < 1$. For the important special case $m = 1$, which might correspond to a smoke oxidation step, there results

$$y(z) = \ln(z/z_i)$$

$$Y(z) = [\ln(Z/Z_i)]/(\gamma s)$$

$$Y^{-1} = Z(Y) = Z_i \exp[Y\gamma s]\ . \tag{10}$$

Finally suppose that there is a regime where ϕ is sufficiently constant that there is a well defined equilibrium value for z (or Z), say z_e, that is approached at a rate linear with the extent of non-equilibrium (i.e., to $z - z_e$ or $Z - z_e$). Hence

$$f(z) = z_e - z$$

Then

$$y(z) = \ln[Z_i - Z_e)/(z - z_e)]$$

$$Y(Z) = \ln[Z_i - z_e)/(Z - z_e)/(\gamma s)$$

$$Y^{-1}(Z) = Z(Y) = z_e + (Z_i - z_e) \exp [Y\gamma s] \ . \qquad (11)$$

INTERPRETATION

The concept of piecewise similar absolute equivalence ratio ϕ histories is sufficiently general to make possible the use of a single model fire for a wide variety of prototype fires. Of course, the entire prototype ϕ range for chemical reactions controlling net smoke production must be included in that of the model. Thus, if the prototype fire includes an important fuel rich reaction zone, say $\phi \sim 3$, then the model must also contain the same fuel rich reaction zone of sufficient extent for appreciable chemical reaction to occur. With this proviso, it is possible in principle for any fire to serve as a model fire for any prototype by choosing a large enough number of ϕ intervals. So far as ϕ history modeling is concerned, the ultimate limit is the extent to which overall fuel and air consumption rates, and overall energy release rate, are exclusively diffusion controlled.

Similarly, treatment of a class of elaborate kinetic models is also possible through specification of a large number of ϕ intervals. Specifically, if a set of N intervals were defined by the sequence of end points $\phi^{(n)}$,

$$\phi^{(0)} > \phi^{(1)} > \ldots > \phi^{(N)} \ ;$$

a corresponding time scale factor $\gamma^{(n)}$, a kinetic rate function $f^{(n)}$, and a rate scale factor $s^{(n)}$ were determined for each $\phi^{(n-1)} > \phi > \phi^{(n)}$ interval; and model smoke concentrations $z^{(n)}$ were known for each condition $\phi^{(n)}$; then the corresponding smoke concentrations $Z^{(n)}$ could be computed via repeated application of Eq. (8), starting with an appropriate initial value $Z^{(0)}$; i.e.,

$$y^{(1)} = \int_{z^{(0)}}^{z^{(1)}} dz/f^{(1)} \; ; \; Y^{(1)} = \int_{Z^{(0)}}^{Z^{(1)}} dZ/[s^{(1)}\gamma^{(1)} f^{(1)}] \; ;$$

$$Z^{(1)} = Y^{(1)^{-1}} [y^{(1)} (z^{(1)})]$$

$$\vdots$$

$$y^{(n)} = \int_{z^{(n-1)}}^{z^{(n)}} dz/f^{(n)} \; ; \; Y^{(n)} = \int_{Z^{(n-1)}}^{Z} dZ/[s^{(n)}\gamma^{(n)}f^{(n)}] \; ;$$

$$Z^{(n)} = Y^{(n)^{-1}} [y^{(n)} (z^{(n)})]$$

$$\vdots$$

$$Z^{(n)} = Y^{(n)^{-1}} [y^{(n)} (Z^{(N)})] \; . \qquad (12)$$

As an example, suppose we wish to model a 3-step smoke production-destruction process. Suppose also that (i) the model and prototype fuels are each reasonably low boiling liquids burning under conditions such that the fuel vapor is initially too cool for significant reaction, so that the effective $\phi^{(0)}$ is the same for model and prototype -- i.e., the maximum for significant pyrolysis -- and $z^{(0)} = Z^{(0)} = 0$; (ii) smoke production is initially zero order -- i.e., $f^{(1)}$ = constant -- until $\phi = \phi^{(1)}$, which is slightly greater than unity; (iii) there follows a short smoke equilibration process toward concentration z_e -- i.e., $f^{(2)} = z_e - z$ -- until ϕ is slightly less than unity; (iv) the smoke oxidizes via a first order reaction -- i.e., $f^{(3)} = z$. Then

$$z^{(1)} = \gamma(1)\ s^{(1)}\ z^{(1)}$$

$$z^{(2)} = z_e + (z^{(1)} - z_e)\ [(z_e - z^{(1)})/(z_e - z^{(2)})\ ]^{\gamma^{(2)}\ s^{(2)}}$$

$$= z_e + (\gamma^{(1)}\ s^{(1)}\ z^{(1)} - z_e)\ [(z_e - z^{(1)})/(z_e - z^{(2)})\ ]^{\gamma^{(2)}\ s^{(2)}}$$

$$z^{(3)} = z^{(2)}\ (z^{(3)}/z^{(2)})^{\gamma^{(3)}\ s^{(3)}}$$

$$= \{z_e + (\gamma^{(1)}s^{(1)}z^{(1)} - z_e)[(z_e - z^{(1)})/(z_e - z^{(2)})]^{\gamma^{(2)}s^{(2)}}\}(z^{(3)}/z^{(2)})^{\gamma^{(3)}s^{(3)}} \qquad (13)$$

Assuming that all of the scaling parameters, as well as the kinetic scheme itself were exactly known, application of Eq. (13) still requires knowledge of three measured quantities, namely $z^{(1)}$, $z^{(2)}$ and $z^{(3)}$. This fact typifies the first major difficulty with any attempt to precisely utilize the modeling formalism set forth in this paper. Because fires of practical interest are invariably turbulent, and subject to wandering and other transient effects of time scale longer than turbulence but too short to follow experimentally, accurate determination of interim smoke concentrations $z^{(n)}$ poses a formidable experimental challenge.

The second major difficulty lies in the fact that piecewise fire scaling is beyond the current state-of-the-art. At present, we are now at the point where, by adjusting ventilation and burning rate, the complete ϕ histories in geometrically similar model and prototype fires can be made the same [8,9]; in terms of characteristic lengths L_m and L_p, respectively, of model and prototype, the time scaling parameter γ is,

$$\gamma = (L_p/L_m)^{1/2} \ . \qquad (14)$$

Use of a fixed time scaling parameter γ does not preclude piecewise kinetic modeling. Even so, the current state of knowledge dictates a cautious approach. Indeed, on the basis of literature available, the authors do not feel justified in putting forward anything other than crude kinetic hypotheses for smoke generation under fire conditions.

The first step in the evaluation of kinetic hypotheses is use of the same fuel for model and prototype fires. Use of reasonably pure, low boiling liquids, say C_{15} or smaller, would insure identical fuel initial conditions.

The simplest chemical hypothesis that can be put forward is that the net smoke production is controlled by a single step, such as zero order production or first order oxidation from an equilibrium state. More generally, if it were possible to continuously vary γ, with the same single controlling step assumed for both model and prototype, then the function f could be inferred directly. Let one particular experimental condition denote the "model," and a sequence of experiments obtained by continuous independent variation of time scale therefrom be regarded as a sequence of "prototypes." For this sequence Z_f (and $dZ_f/d\gamma$) would be experimentally determined functions of γ, with $Z_f = z_f$ at $\gamma = 1$. Then, rewriting Eq. (8) and using Eq. (6), with s=1, yields

$$\int_{z_i}^{z_f} dz/f(z) = \left[\int_{Z_i}^{Z_f} dZ/(f(Z))\right]/\gamma = \text{constant} \tag{15}$$

or

$$f(Z_f) = C\, dZ_f/d\gamma, \tag{16}$$

where C is an unknown, and for scaling purposes unneeded, constant. It is noted that the final result, Eq. (15), is independent of the initial concentration z_i and Z_i, if indeed net smoke production is controlled by a single kinetic step; i.e., either the integrals in Eq. (15) are effectively independent of z_i and Z_i, or $Z_i \equiv z_i$. Thus, the uniqueness of $dZ_f/d\gamma$ versus Z_f or lack thereof constitutes a test for the existence of a single phenomenological kinetic step which controls net smoke production.

For practical fire modeling, in which even approximate smoke production data is badly needed, there exists a powerful incentive to live with such a simple model if at all practicable. Unfortunately, although variation of γ via length scaling is technically feasible, it is expensive even to obtain a few "prototype" points. If as many as two such prototype points can be obtained, it is possible to fit some of the more likely forms of f(z), such as z^m, to obtain a preliminary estimate. This estimated function f could then be tested by repeating other length scaled experiments from "model" starting points with different ventilation and burning rates.

Still further information could be obtained, if we could quantify the effect on absolute equivalence ratio history $\phi(t)$ of independent variation of ventilation or burning rates. Hopefully the main effect would be describable by a shift in time scale, perhaps by different magnitudes on the fuel rich ($\phi > 1$) and lean ($\phi < 1$) portions of the fire. If a single kinetic step did in fact control the production of the smoke constituents of interest, then it would only be necessary to experimentally determine the variation of time scale (i.e., of γ) with respect to ventilation or burning rate in the appropriate ϕ regime.

If the single kinetic step hypothesis fails, then a simple 2-step reaction (e.g., production/oxidation) should be investigated. By varying length scale, ventilation rate, and burning rate independently, it should be possible to evaluate the required parameters. Such a process cannot be as straightforward as that described above for single step models, and will almost certainly require data-in-hand to discuss fruitfully.

A final potential difficulty worth mentioning is a consequence of the fact that some fuels of practical interest pyrolize in a chemically non-unique manner. For example there is considerable evidence[10,11] that cellulose pyrolizes by two chemically distinct routes which yield chemically distinct pyrolysis products depending on the thermal history of the solid fuel. Thus steps, such as fuel heating or fuel bed geometry alteration, taken to alter the burning rate of fuels which undergo condensed phase pyrolysis reactions may inadvertently alter the initial concentration $z^{(0)}$ of a smoke constituent or, worse, may completely alter the smoke producing chemistry.

CONCLUDING REMARKS

1. We have outlined a scheme for modeling smoke production in enclosed fires. The assumptions underlying this formalism certainly preclude the precise application of detailed elementary-step chemical kinetics. But we believe that the simplified phenomenological approach proposed is consistent with the state of fire research as a whole, and may well succeed in providing some of the most badly needed answers.

2. Despite the gross simplifications in this modeling formalism, substantial experimental work must be accomplished before the scheme will be useful.

3. Although the modeling formalism was developed for enclosed fires and discussed with these in mind, it applies also to open fires.

4. Respecting the particulate matter in smoke, we have deliberately avoided mention of the proper measure of the smoke concentration. This might be a mass concentration, a mean optical absorption coefficient, or some other quantity. Since a phenomenological approach is used, any convenient compromise between kinetic simplicity and ease of measurement can be adopted. Also, nothing in the proposed scheme or our discussion of it precludes application to unwanted gas species which accompny smoke, such as carbon monoxide.

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